A stakeholder-grounded evaluation of the seven functions model of technological innovation systems theory in UK offshore wind and marine renewables.

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A STAKEHOLDER-GROUNDED EVALUATION OF THE “SEVEN FUNCTIONS” MODEL OF TECHNOLOGICAL INNOVATION SYSTEMS THEORY IN UK OFFSHORE WIND AND MARINE RENEWABLES

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Abstract

Technological Innovation Systems theory provides a useful framework with which to consider energy transitions. The "seven functions" framework allows researchers to examine the progress of emergence of new technologies but has not hitherto been tested for completeness and validity with stakeholders in an energy transition.

The emergence of offshore wind over the last 20 years in the UK has been a significant part of the UK's energy decarbonisation transition, and has provided the industrial roots for this research.

The research has critically evaluated the "seven functions" model of TIS with stakeholders in the offshore renewable energy sector in the UK, with the aim of assessing whether each of the seven functions is necessary, and whether together they are sufficient to explain the development of a TIS.

This thesis has reviewed the literature to find that no canonical inventory of seven functions exists, and it develops one.

Using interviews with more than 30 influential participants in the offshore renewables sector, including project and technology developers, policy makers, supply chain, support organisations and other stakeholders, the thesis examines whether the seven functions provide a "necessary and sufficient" framework to characterise the emergence of offshore wind and marine renewables (tidal stream and wave) in the UK since 2000.

The research supports the seven existing functions, and finds evidence for a new function, which is defined as "relative value potential". RVP considers the potential or actual value offered by an emergent technology, to consider whether it can demonstrate a roadmap to achieving an unsupported viability.

sTIS is far from unique in theories for understanding socio-technical transitions. This thesis also finds that the proposed new function offers some scope for a reconciliation of TIS and another leading theory in this space – Multi-Level Perspective.

The thesis concludes by eliciting learnings from the emergence of offshore wind for the benefit of tidal stream and wave energy developers.

Key words: transition theory, TIS, functions, offshore wind, marine renewables, validity

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Glossary

BCE – Before Common Era

BEIS – HM Government, Department of Business, Energy and Industrial Strategy

BG – British Gas plc

CCGT – Combined Cycle Gas Turbine power generation

CEGB – Central Electricity Generating Board

CfD – Contract for Difference

CO_2 – Carbon Dioxide

DONG – now Ørsted

EdF – EdF Energy – (subsidiary of Electricite de France SA)

EMEC – the European Marine Energy Centre

EMR – Electricity Market Reform

EnBW - EnBW Energie Baden-Württemberg AG

Eon – Eon Energy _ (subsidiary of E.ON SE)

EOWDC – European Offshore Wind Deployment Centre

EU – European Union

EU ETS – European Union Emissions Trading System

EWEA – European Wind Energy Association

FCOE – Full Cost of Energy

FID Enabling / FIDER – Final Investment Decision Enabling for Renewables contract arrangements

GE – General Electric

GVA – Gross Value Added

GW – Gigawatt (1000 MW)

GWh – Gigawatthour

ICfD – Innovation Contract for Difference (a funding proposal being made by the Marine Energy Council for emergent tidal stream and wave technologies)

IOC – International Oil Company

IP – Intellectual Property

IPCC – Intergovernmental Panel on Climate Change

LCOE – Levelised Cost of Energy

LIDAR – Light Detection And Ranging

kW – kilowatt

M&A – Mergers and Acquisitions

MLP – Multi-Level Perspective

MRDF – Marine Renewables Development Fund

MW – Megawatt (1000 kW)

MWh – Megawatthour

NASA – National Space and Aeronautical Administration

NDC – Nationally Determined Contribution

NHS – National Health Service

NIMBY – “Not In My Back Yard”

NOx – Nitrogen oxides

OEM – Original Equipment Manufacturer

ORE Catapult – Offshore Renewable Energy Catapult

OSBIT – OSBIT Limited, an engineering company

PM2.5 – Atmospheric particulates with diameter less than 2.5 micrometres

R&D – Research and Development

RET – Renewable Energy Technology

RO – Renewables Obligation

ROC – Renewables Obligation Certificate

RWE – RWE Npower plc (subsidiary of RWE AG)

SCC – Social Cost of Carbon

SDP – Social Democratic Party

SMART award – Small firms' Merit Award for Research and Technology Award

SNM – Strategic Niche Management

SOx – Sulphur oxides

SPC – Social Price of Carbon

SSE – Scottish and Southern Energy plc

TIS – Technological Innovation Systems

TM – Transition Management

TRL – Technology Readiness Level

UK - United Kingdom of Great Britain and Northern Ireland

UNEP – United Nations Environment Programme

UNFCCC – United Nations Framework Convention on Climate Change

VC -Venture Capital

WMO – World Meteorological Organisation

WTG – Wind Turbine Generator

1 Introduction

Transitions in energy systems have occurred many times, and with increasing frequency, over humankind's time on Earth. The latest transition – the decarbonisation transition – has different characteristics and is important for the continuing survival of society in its current form.

Transition theory offers a useful theoretical framework with which to understand energy transitions; this research has critically evaluated an important aspect of this theory.

Since 2000, the emergence of offshore renewable energy has been a critical element of the UK's energy decarbonisation transition. This example of a socio-technical transition was seen to offer a basis for interesting research into the process of socio-technical transition.

1.1 Research aims

The application of transition theory to the emergence of offshore renewable energy has provided a rich theme for research. The principal research aim is to explore how the application of transition theory to the emergence of new technologies helps to understand the factors enabling and blocking this transition. The comparison of offshore wind compared with wave and tidal stream technologies provides an interesting field of study, as functionally similar technologies have achieved different levels of success.

As a subsidiary aim, the effectiveness of transition theory in developing this understanding was also assessed.

1.2 The importance of energy

Life on earth relies on energy absorbed directly from the sun (photosynthetic organisms) or from hydrothermal vents (chemosynthetic bacteria) or from the consumption of other organisms. Uniquely, *Homo sapiens* has learned to exploit energy sources outside the body (described by Price [1] as "extrasomatic"), allowing humankind to colonise every continent and to exploit and modify the environment for its own benefit.

Over time, the exploitation of extrasomatic energy sources has developed from fire (burning wood, peat and animal dung for heating and cooking) to sophisticated energy generation and distribution systems enabling all of the complexity of modern life. This has allowed humankind to take a dominant position among all species, with the ability to shape the environment, to feed itself more effectively (enabling the development of language, culture and technology) and to inhabit otherwise uninhabitable ecological niches.

These energy systems now involve the extraction and use of fossil fuels – coal, oil and gas – for transport, heating and power generation, the use of nuclear energy for electricity generation (and weapons materials) and more recently the development of renewable power generation technologies and electric, hybrid and other low-carbon vehicles.

Price [1] states that the use of extrasomatic energy sources is equivalent to every person on Earth being able to benefit from the work equivalent to around 50 other people. In the most technologically advanced and energy-hungry society – the US - he says that each individual benefits from the work equivalent to 200 "ghost slaves". In pre-industrial societies, dominant parts of society could achieve similar benefits through slavery, but the ratios were never as high. In Roman Italy, for example, it is suggested [2,3] that there were 1-1.5 million slaves to serve a population of 4-5 million free citizens. Humankind is using, both per head and in total, more energy than ever before.

Since the adoption of fire, humankind's use of extrasomatic energy has undergone a number of transitions. Until the current transition - "the decarbonisation transition" - these have shared the critical feature of being driven by "market pull", where the consumers of energy recognise and adopt the benefits of the energy technologies, although as society gained in complexity these benefits have not necessarily been equitably shared.

1.3 Energy transitions

1.3.1 Pre-industrial to industrial

Burning biomass, whether trees or animal waste, has been (and remains) an important source of energy for heating and cooking. First believed to have been used at least 1.5 million years ago [4], the use of fire for cooking remains an important source of energy for nomadic communities and other areas with no access to other resources.

In a pre-industrial and heavily fragmented society, there was no government and therefore no policy to govern or guide the transition to biomass burning, which was driven by the clear benefit it offered to users (such as warmth, cooking and protection from predators). It can legitimately be characterised as a market pull-driven transition.

Mankind also learned to exploit other concentrated natural sources of energy: animal-powered water wheels to lift water for irrigation are known in ancient Egypt (4th century BCE) [5]; tidal mills existed in Roman times [6]; the earliest wind mills for grinding cereals and pumping water were developed in eastern Persia in the 9th century [7], and the use of domesticated animals for agriculture and transport emerged even earlier.

These technologies which exploit natural energy sources offered clear advantages over previous ways of doing things and required no policy or governmental support. Again, they represented a market pull-driven transition.

1.3.2 The first industrial revolution – coal

The first industrial revolution, starting in the UK in the late 18th century, relied on coal as its energy source. As well as using coal for cooking and heating, coal was primarily used as the energy source for generating steam, which was then used to power industrial machinery (such as woollen mills and water pumps for mines) and later railways [8].

This transition required no explicit governmental support, as those able to invest in the technology did so, and many people moved from agricultural work to industrial work in the rapidly-growing cities to earn higher wages than those previously available to agricultural workers.

1.3.3 The transition to oil

Whale oil began to play a role in lighting from the 1700s, but it was not until the 1859 discovery of large quantities of crude oil at Titusville in Pennsylvania by Col. Edwin Drake [9] that petroleum and its products began to play a significant role in the energy system.

While lighting and lubrication were the early markets for petroleum products, it was the emergence of the internal combustion engine, which combined innovations by Lenoir, Otto and Diesel [8], which triggered the rapid growth of the market.

The advantages offered by the use of oil, in particular for lighting and personal transport, were compelling, and once again market pull was sufficient to drive the transition to oil.

1.3.4 The role of electricity

Since the first local electrical distribution networks were deployed in the 1880s, electricity has become an essential feature of the modern world. It is used in many roles: to cook, to light and to heat, to provide services, transport and entertainment, and even to create currency through cryptocurrency “mining”.

In the UK, the National Grid and local distribution networks connect generators and consumers, balancing supply and demand to deliver voltage and current within tightly-defined specifications to users from Land’s End to Shetland.

This system has evolved in parallel with societal needs, commercial pressures and political choices. Up until the 1990s, electricity generation in the UK was dominated by coal-fired stations operated by a national utility – the Central

Electricity Generating Board (CEGB), with a limited contribution from nuclear and from hydro power in northern and western Scotland [10].

In the 1990s, response to political choices – specifically the break-up and privatisation of the CEGB into Npower plc, PowerGen plc, ScottishHydro plc and ScottishPower plc – the generation system began to deploy gas fired power stations in a process known as "the dash for gas" [10] (see Figure 1-1).

More recently, since 1992, renewables additional to hydro, including offshore and onshore wind and biomass, have also begun to contribute substantially to the UK energy mix and coal and oil-fired generation have been much reduced (see Figure 1-1.).

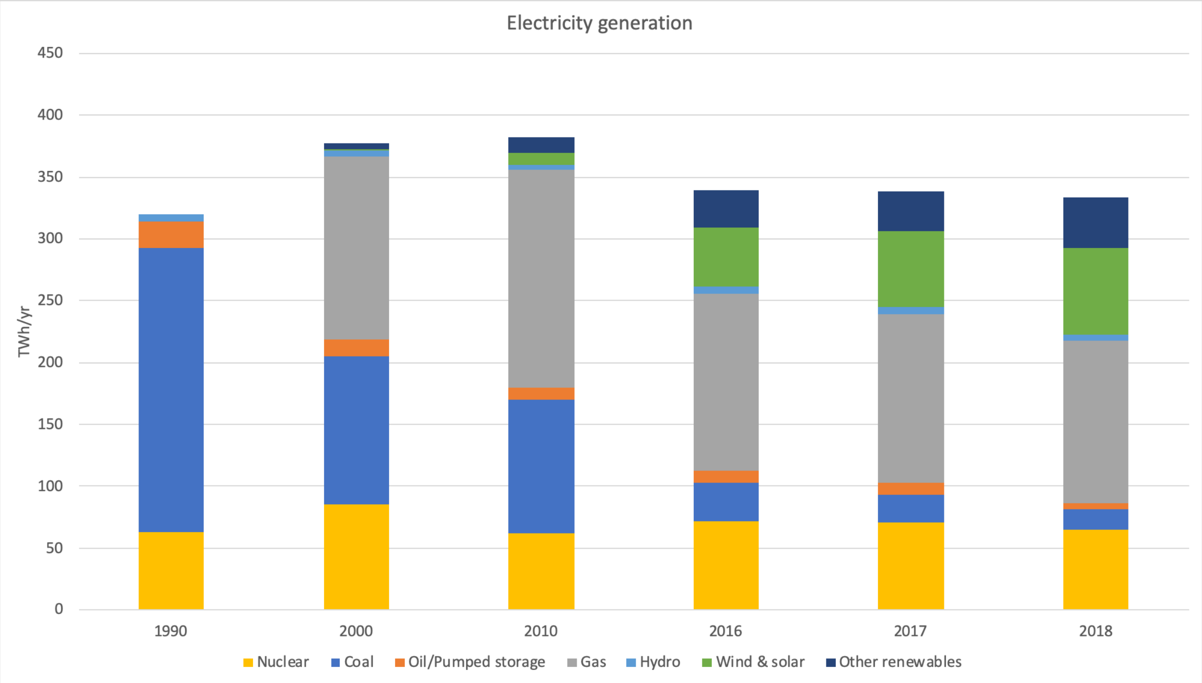

Figure 1-1: Electricity generation in the UK since 1990; author's analysis from data in [11,12]

The role of coal has been much reduced over recent years, as clearly shown by a graphic in the Guardian newspaper [13], which shows how the UK has moved from a reliance on coal in 2012 to achieving long periods with no coal-burning in 2019 (Figure 1-2.). The UK Government has now committed to closing all coal-fired power generation by 2025 [14].

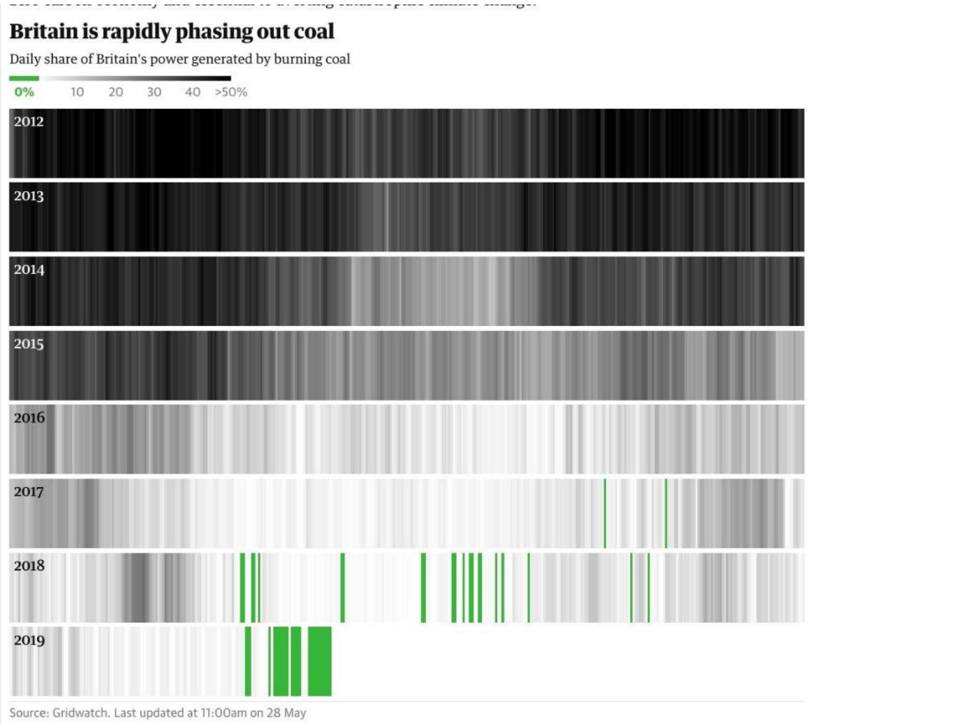

Figure 1-2: Daily share of Britain's power from coal; source [13]

1.3.5 A more diverse picture

Following the oil crises of the 1970s, the industrialised world began to seek to reduce its dependence on oil, and this led to growth in gas-fired and nuclear-powered electricity generation (although personal mobility continued to rely almost exclusively on oil). The details of this transition are beyond the scope of this research, but have been explored in some detail by others (e.g. Foxon [8]).

It can be summarised that this transition relied on both market pull (due to price signals and fear of continuing price volatility) and techno-economic push (in which other technologies became cost-comparable with the prevailing oil-based paradigm).

1.4 The decarbonisation transition

1.4.1 Greenhouse gases and climate change

Modern greenhouse gas/climate change science first emerged in the 1960s, when Manabe and Wetherald identified the impact of CO_2 on atmospheric temperatures [15].

At around the same time, the Club of Rome's 1972 report – "The Limits to Growth" [16] did much to publicise the debate about sustainability, although it was primarily concerned with the impact on human civilisation of shortages of natural resources, rather than with the excess emissions of carbon dioxide and other greenhouse gases which have now become the focus of current international policy attention.

In the 1980s, public interest in environmental matters began to increase rapidly. Rootes and Miller [17] describe the mid 1980s as the "fourth phase" of the growth of Environmental Movement Organisations (EMOs), during which membership numbers increased rapidly and a number of new and increasingly radical organisations emerged.

Political recognition and acceptance of climate change and the potential role of renewable sources of energy as a matter of public interest broadly paralleled the public view. Climate change and renewable energy were first mentioned in the Labour and Liberal/SDP Alliance party manifestos for the 1983 General Election (which was won by the Conservatives) [18-29]. By the 1987 election, all of the major UK-wide parties made explicit reference to renewable energy in their manifestos [30-32], and by 1992, public knowledge of the subject was clearly enough for the Conservatives to state that "The world's resources of fossil fuels will come under increasing strain during the 21st century; so may the global environment if the build-up of carbon dioxide, the so-called "greenhouse effect", significantly raises temperatures and changes climates" [33-35].

In response to the growing weight of scientific evidence and analysis, and public interest and support, the InterGovernmental Panel on Climate Change (IPCC) was formed in 1988 under the auspices of the United Nations [36]. It was established by the precursor organisations of the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP), and exists to "provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation" [36].

The IPCC states that "IPCC assessments provide a scientific basis for governments at all levels to develop climate-related policies, and they underlie negotiations at the UN Climate Conference – the United Nations Framework Convention on Climate Change (UNFCCC)." [36]

1.4.2 Consensus emerges

Since its first report in 1990, which formed the basis for the UNFCCC, the IPCC has released five assessment reports. The fifth assessment report [37], published in 2014, concluded unequivocally that "human influence on the climate systems is clear", and that "recent climate changes have had widespread impacts on human and natural systems". It further concluded that "anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth…and their effect, together with those of other anthropogenic drivers, are extremely likely to have been the dominant cause of the observed warming since the mid-20th century".

Despite the continuing vocal presence of a limited number of "climate change deniers", the settled weight of academic opinion supports the IPCC conclusions. NASA reports that in "multiple studies published in peer-reviewed scientific journals show that 97 per cent of more actively publishing climate scientists agree…climate warming trends over the past century are extremely likely due to human activities" [38].

1.4.3 Steps to implementation

In the light of the settled scientific position, nations have been taking steps to address the problem of climate change, through the introduction and adoption of a number of conventions and protocols. These include the Kyoto protocol (1992) [39], at which broad outlines of emissions targets were set, and the Paris Agreement (2015) [40], which established that the ratifying countries would set emissions targets with the intent of limiting global average temperature rises to 2 °C.

In May 2016, the UNFCCC published a Synthesis Report [41], which considers whether the likely effect of the National Determined Contributions (NDCs) which had been indicated before April 2016 is sufficient to meet the objective of limiting the increase in global temperatures to 2 °C.

Critically, the Synthesis Report concludes (paragraph 42), that "much greater emission reduction efforts than those associated with the Intended NDCs will be required in the period after 2025 and 2030 to hold the temperature rise below 2 °C above pre-industrial levels”.

It is clear that the decarbonisation transition is well under way, and further efforts can be expected to maintain momentum in this direction.

1.5 UK and the decarbonisation transition

The United Kingdom is party to the collective European Union carbon emissions reduction plan (the EU NDC). A senior Government official, the special representative for climate change and the Foreign Office, has confirmed that “existing legislation will dictate Britain’s climate ambition and ‘that will not change with Brexit’” [42].

In launching the Clean Growth Strategy, Claire Perry, the Minister of State at the Department for Business, Energy and Industrial Strategy, confirmed the UK’s commitment to addressing climate change [43]. In doing so, she set out a new “triple test” which the Government would apply in considering whether to support new technologies. The three tests are:

- “First, does this deliver maximum carbon emission reduction?
- Second, can we see a clear cost reduction pathway for this technology, so we can deliver low cost solutions?
- And third, can the UK develop world-leading technology in a sizeable global market?” [43].

This triple test reflects the tensions implicit in energy and energy innovation policy, first clearly expressed by then-Secretary of State for Business, Innovation and Skills, Vince Cable. Cable summarised the trilemma thus: “We are facing a trilemma. As well as reducing emissions and improving energy security, we need to reduce costs for energy users” [44].

Since then, this thinking has been developed to recognise that another factor should also have a bearing – the question of which national economy benefits from the spend made on innovation [45]. Accordingly, there is an energy *quadrilemma* comprising the four features of decarbonisation and emissions targets, security of supply, cost of energy and local content/Gross Value Added (GVA).

1.6 The UK energy "quadrilemma"

1.6.1 Decarbonisation and emissions targets

The UK is legally required to achieve overall emissions reductions targets, both by its commitment to the Paris Agreement and by domestic law in the form of the Climate Change Act. Within these constraints, policy options are open to the UK and (to a lesser extent) the Scottish, Welsh and Northern Irish Governments.

The Government's imposition of the "triple test" indicates that economic factors, and specifically the cost of carbon abatement, will be a key determinant in informing policy decisions. However, the importance of wider political factors can never be disregarded, as indicated by the UK Government's withdrawal of support for onshore wind – arguably the cheapest source of zero-carbon power available.

1.6.2 Security of supply

It is axiomatic that a Government which allows the lights to go out will lose support with the electorate. Accordingly, Governments are keenly interested to ensure that energy supply is secure, and that the electricity system must remain available at all times.

There are a number of factors impacting security of supply, including the increasing intermittency of power generation as renewables increase, the role of storage and frequency response solutions, the requirement for baseload power (and the role of nuclear in this) and the retirement of aged or high-carbon capacity in response to decarbonisation targets.

1.6.3 Cost of energy

Energy poverty is a third factor of importance to Governments. It is obviously politically damaging for any fraction of the population to be unable to heat their homes in winter, and any Government which allows (or causes, through policy) significant increases in power costs is likely to lose support.

The implementation of the Renewables Obligation, which added the costs of renewable support to consumers' bills, had some price-increasing effect, and this led the Government to reconsider appropriate mechanisms to support the decarbonisation agenda.

1.6.4 Local content and Gross Value Added

The decarbonisation of UK electricity generation is likely to involve expenditure in the order of many tens of billions of pounds. It is a legitimate question for Government to be concerned with how much of this value remains in the UK, and how much expenditure "leaks" to outside the UK. In the post-Brexit context, this may become even more important.

BVG Associates, a consulting firm, has proposed a methodology in which the GVA contribution of decarbonisation expenditure is considered in assessing investment choices. The offshore wind sector, where the majority of decarbonisation spend is likely to occur, is already alert to this, and both developers and the trade association, RenewableUK, are working to ensure that this sector can make an acceptable case in relation to this leg of the energy quadrillemma [46]. The offshore wind sector, which has recently agreed a "Sector Deal" with Government, has set a target of 50% UK content in new offshore wind farms [46,47].

It is within the context of the energy quadrilemma that the emergence of offshore wind and the potential emergence of tidal stream and wave energy in the UK electricity system must be considered.

1.7 The development of offshore renewables in the UK

The first UK offshore wind farm, Blyth in Northumberland, was deployed in 2000 [48]. Since then, the offshore renewable energy technologies of wind (both fixed foundation and floating), tidal stream and wave energy have undergone divergent development trajectories. This has been due to a combination of technological, economic and political factors, and exploring these has formed the basis of this research.

It is useful to set out the broad context in which the emergence of offshore renewable technologies in the UK has been set, including the factors defining the "energy quadrilemma" discussed in Section 1.6.

1.7.1 Political framework

UK political support for renewables exists within a broader framework of EU and international decarbonisation initiatives and structures. At the international level, the 1997 Kyoto Protocol, established by the parties to the United Nations Framework Convention on Climate Change [39], set specific carbon emissions reduction targets for the developed countries. In response to Kyoto, the European Union set an aggregated reduction target of 8% relative to 1990 levels [49].

The 2015 Paris Agreement strengthened previous international commitments to carbon emissions reductions. Its intent is to have parties put in place programmes to ensure that global temperature rise is limited to 2 degrees Celsius above pre-industrial levels [40]. The Paris Agreement came into force when 55% of parties had ratified, on 4th November 2016.

Successive UK Governments have supported these international and European initiatives with a sequence of Energy Acts [50-52] and policy instruments to deliver these objectives.

1.7.2 Financial support

The principal successive policy instruments intended to deliver increasing renewables capacity, whilst not entailing excessive cost for consumers or the taxpayer, were the Non-Fossil Fuel Obligation, the Renewables Obligation and Contracts for Difference.

1.7.2.1 Non-Fossil Fuel Obligation

The Non-Fossil Fuel Obligation aimed to encourage "demonstration of renewable energy technologies that are approaching commercial competitiveness". It was "hoped that, once established, these technologies will be viable without further support" [53].

Under the NFFO Orders (the first of which was known as NFFO1), generators were awarded fixed price, index-linked contracts for their generation at a premium to conventional electricity prices; this premium was underwritten by the revenues of the Fossil Fuel Levy [53].

The first NFFO order, NFFO1, was successful in bringing on renewable capacity and was followed with four further orders in England and Wales (NFFO2-5), three orders in Scotland (Scottish Renewables Orders, SRO1-3) and two in Northern Ireland (Northern Irish Non-Fossil Fuel Orders, NI-NFFO1 and 2) [53].

Only one offshore windfarm, Blyth Offshore (capacity 4 MW) was commissioned under the NFFO regime (NFFO4) [53]. Although one wave project was awarded a SRO contract, no wave or tidal stream projects were delivered under the NFFO, SRO or NI-NFFO orders,

As delivery of capacity under the NFFO regime was insufficient in the context of the Kyoto Protocol – it reached 5% of UK electricity production – Government set an increased target of 10% of power from renewable sources by 2010 [53] and introduced the Renewables Obligation ("RO") as the mechanism to drive this capacity.

1.7.2.2 Renewables Obligation

The RO, introduced in 2003, placed an obligation on Public Electricity Suppliers to source a defined and increasing percentage of their electricity from eligible renewable sources. If they failed, they were required to buy Renewable Obligation Certificates ("ROCs") from renewable generators or from ROC traders or pay a "buyout" price to Ofgem. A similar Obligation was introduced in Northern Ireland. The total of buyout payments was recycled to those suppliers which had submitted certificates, providing an incentive to comply with the Obligation [54].

The percentage of electricity supply covered by the RO was set at 3% in 2003, rising to 15.4% in 2016 [55].

While the Non-Fossil Fuel Obligation offered different prices to different technology tranches, the Renewables Obligations did not initially differentiate between technology types. The most important change adopted in the Energy Act 2008, was the "banding" of the RO, increasing the level of support to those technologies which needed it most and limiting support to already-viable technologies [52], thereby minimising the overall costs of the scheme. ROC banding effectively doubled support to offshore wind, which received 2 ROCs/MWh, and increased support for wave and tidal to 5 ROCs/MWh.

In response to increasing cost of the RO – due in large part to the increase in offshore wind capacity - the Government announced reform of the UK Electricity Market to "deliver low carbon energy and reliable supplies, while minimising costs to consumers" ("EMR") [56]. EMR included the replacement of the Renewables Obligation with a new Contracts for Difference ("CfD") scheme.

As at August 2019, 6,570 MW of offshore wind were operating under the RO [57].

1.7.2.3 Contracts for Difference

CfDs were announced as part of EMR in 2015 [56]. In general terms, the contracts guarantee wind farm developers a defined unit price for electricity generated (called the "strike price") which would increase in line with the Consumer Price Inflation (CPI) index. The mechanism is that the Government-owned Low Carbon Contracts Company ("LCCC") pays an amount to the generator in a year in which the market price is less than the strike price, and if and when the market price exceeds the strike price, the developer pays the balancing amount to the LCCC.

Critically, wave and tidal stream were categorised with offshore wind in "Pot 2" of the CfD scheme, meaning that they had to compete directly on the basis of cost for contracts with offshore wind. This had the effect of rendering wave and tidal stream schemes unable to secure funding support.

Early projects were granted CfDs under the FIDeR (Final Investment Decision Enabling for Renewables) awards of contracts, at administratively-set (rather than competitively-bid) prices from £140-150/MWh comparable with the level of support under the RO [58]. It was recognised that these prices might be "higher than needed" [59], but that it was nevertheless considered desirable to maintain a stream of offshore wind.

Round	Strike price	Projects
FIDeR awards	£140-150/MWh (administratively set)	Beatrice, Burbo Bank Extension, Dudgeon, Hornsea 1, Walney Extension, amounting to 3.2GW
First allocation round	£119.89/MWh £113.97/ MWh	East Anglia 1 (714 MW) Neart na Gaoithe (448 MW) [60]
Second allocation round	£74.75/MWh £57.50/MWh £57.50/MWh	Triton Knoll (860 MW) Moray East (1,116 MW) Hornsea 2 (1,218 MW) [61]
Third allocation round	Maximum strike price £53-56/MWh Bids at £39.65/MWh	Maximum strike price announced for late 2019, bids announced late 2019 [193]

Table 1-1: CfD allocation rounds and strike prices (author's analysis)

As of August 2019, 1,913 MW of capacity were operating under the CfD regime with another 15 GW in the pipeline [57,62].

The actual cost of offshore wind has varied through time, as experience and learning curve effects are offset by technological challenges of larger turbines in deeper water, as shown by Aldersey-Williams et al. [63], but anticipated cost reduction trends demonstrated by CfD strike prices are clearly downwards. The competitive nature of the CfD bidding process is likely to have been a factor in driving down prices for the generated electricity from offshore wind. If delivered, these cost reductions are likely to to "strand" wave and tidal stream projects, which are unable to compete with prices at these levels.

1.7.3 Technology development

Offshore wind, wave and tidal stream technologies have shown divergent development paths over the last 20 years.

1.7.3.1 Offshore wind

The core offshore wind technology of three-bladed axial flow horizontal axis wind turbine generators ("WTGs") was already well established as an onshore technology by 2000 [48],, although typical WTG capacities at that time were 1 MW or less. Over the two decades, development has focussed on increasing capacity, improved installation and maintenance techniques.

While the first offshore windfarm, Vindeby in Denmark, deployed 450kW WTGs [48], typical WTG capacity has now increased to around 8-9 MW, with GE recently announcing a 12 MW variant [64]. This upscaling has been a large major factor in cost reduction, as the installed capacity per foundation structure and installation operation has markedly increased. Technological innovation has also occurred in installation techniques and vessels, to accommodate mass deployment of larger WTGs, and maintenance strategies have evolved to deal with larger windfarms, further from shore [65].

As of August 2019, a total of 8.5 GW MW of offshore wind capacity has been commissioned under the RO and CfD schemes. The CfD scheme has also given rise to another 2.9 GW of capacity under construction and a further 12.1 GW consented [62].

More recently, the deployment of WTGs on floating foundations has demonstrated the technical viability of deeper water wind farms, potentially opening up much larger resource areas for development [66].

1.7.3.2 Wave

Wave technologies are extremely diverse with no dominant design paradigm. The RICORE project [67] found 96 different wave energy technologies, but only 30 of these were considered to have Technology Readiness Levels (TRL) above 5. A number of full-scale and part-scale wave energy devices have been tested at the European Marine Energy Centre ("EMEC") [68], but commercial deployment has not yet happened.

Pelamis Wave Power achieved the commercial sale of variants of its device [69], but this sector-leading company failed in 2014, citing an inability to raise finance and slower than hoped development progress [70]. MacGillivray [71] suggests that part of the difficulty for wave (and tidal stream) developers is that they failed to iterate designs at small (and cheap) scale.

Following the failure of Pelamis, the Scottish Government established Wave Energy Scotland to "ensure that Scotland maintains a leading role in the development of marine energy" [72]. Despite these efforts, the commercial emergence of grid-scale wave energy technologies has yet to happen and the only grid-connected capacity known is Wello's sub-MW Penguin device at EMEC [68].

1.7.3.3 Tidal stream

EMEC's tidal stream test facilities were not available until two years after wave test facilities [73], suggesting that wave was seen to be leading tidal stream in the early 2000s. It now appears that tidal stream technologies have taken a lead over wave in development, as multiple technologies have now demonstrated extended periods of reliable grid-connected generation (e.g. Orbital Marine, formerly Scotrenewables) [73] and Atlantis [74] and some features of a dominant design paradigm are emerging.

Although developers differ on whether floating or seabed-mounted turbines are preferred, the leading companies of Orbital Marine Power, SIMEC Atlantis and Nova Innovation have converged on upstream axial flow horizontal axis turbines [75].

A total of less than 10 MW has been installed in the UK – 6MW in phase 1A of Meygen [74], together with a number of prototype machines of up to 2MW capacity at EMEC [73].

The actual and anticipated cost reductions in offshore wind, and the opening of deeper water resource areas to floating wind present significant challenges to wave and tidal stream. Although tidal stream has secured some funding support and is increasingly deploying in more supportive territories (e.g. Canada, France), wave energy development appears to be faltering as a path to commercial viability is not clear.

1.8 Offshore wind, wave and tidal stream as part of the UK energy mix

Since 2000, the addition of more than 20 GW of onshore and offshore wind has made a significant contribution to power generation in the UK. The addition comprises around 8.5 GW of offshore wind, and nearly 13 GW of onshore wind, although it is important to note that onshore wind typically operates at a lower capacity factor than offshore wind, meaning that their contributions to output are currently approximately equal [12].

Figure 1-3 shows the increasing contribution of "non-thermal renewables" to the UK electricity mix [76]. Non-thermal renewables comprise hydro, offshore and onshore wind, solar and wind. The largest contributors to this are onshore wind (installed capacity 13 GW) (as at August 2019 [62]).

The contribution of the non-thermal renewables is made up of onshore and offshore wind and solar photovoltaic generation as shown in
. The growth of solar rapidly increased after 2013, when the combination of an attractive feed-in tariff regime and the availability of low-cost solar panels became favourable [77]. This rate of installation was abruptly and severely reduced when the Government cut feed-in tariff support in 2016.

Despite a reduction in UK Government support for onshore wind, capacity has continued to be added over the period, although the rate of capacity addition is expected to fall as the subsidy regime and political climate become less attractive. RenewableUK's UKWED database [78] shows less than 10 GW of onshore wind in the planning process, as compared with nearly 30 GW offshore.

Offshore wind has shown similar capacity growth as onshore wind and solar, but this is expected to continue into the future, as the Sector Deal [47] anticipates 30 GW of capacity installed by 2030 and 50 GW by 2050, based on the Government's commitment to continuing support.

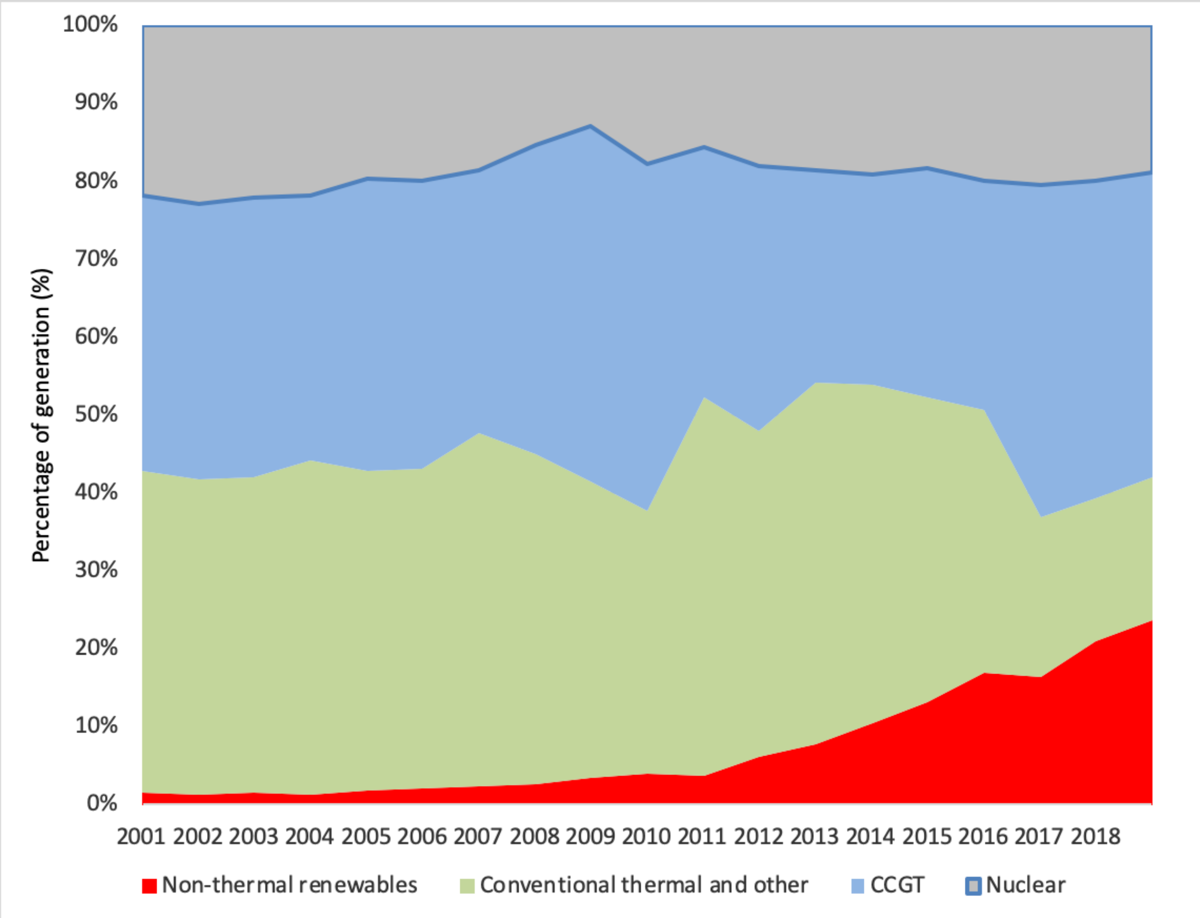

Figure 1-3: Percentage of electricity supplied by generation technology; source [12]

Combining data on installed capacity from Energy Trends, table 6.1 [12] and average capacity factors[1] from table 6.4, the generation from these technologies can be estimated. On that basis, offshore and onshore wind now contribute approximately equally to electricity generation, while solar represents a smaller fraction (see Figure 1-4).

As Figure 1-4 shows, all three of the main renewable technologies showed strong growth during the period, but growth in onshore wind and solar is slowing, while offshore wind continues to accelerate. This may be explained by the changes in support for the technologies. Onshore wind was the first technology to deliver

[1] Also sometimes known as load factor, capacity factor is calculated as average generation over a period, divided by maximum potential generation at nominal or "nameplate" capacity. Over 2017, capacity factors for offshore wind, onshore wind and solar respectively were 38.9%, 28.0% and 10.7% [12].

significant generation, as the RO as initially structured offered viable returns [79]. The closure of the RO to new generation in 2017 correlates with an abrupt slowing in new onshore capacity: RenewableUK was prepared to say that the closure was the cause of the slowdown [80]. Similarly, solar installations increased sharply when the Feed-In Tariff was introduced, and slowed when the FIT was withdrawn [81].

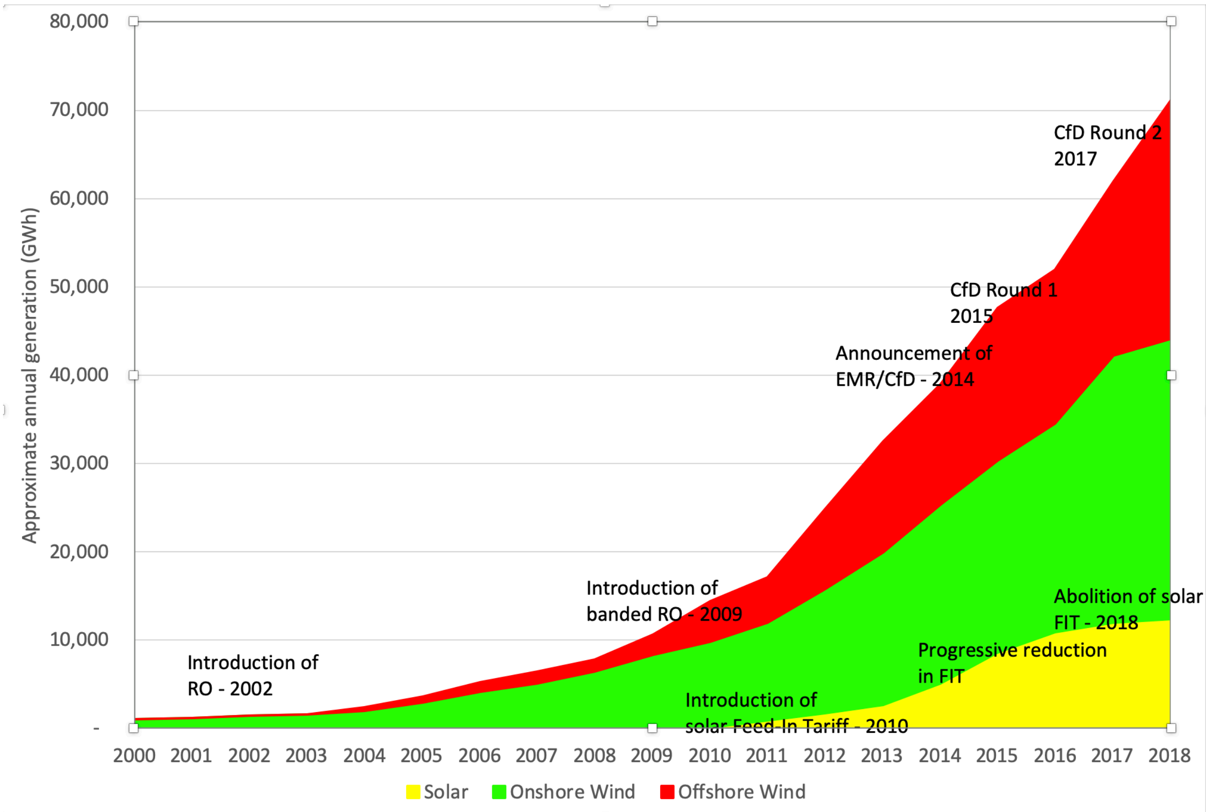

Figure 1-4: Estimated annual generation by technology; derived from [12,78]

Offshore wind is expected to show a continuing growth trend, as the Sector Deal commits the industry to delivering further significant capacity with the Government offering future CfD support [47].

1.9 Structure of this thesis

Drawing all of these threads together it is clear that the comparative evolution of offshore wind, tidal stream and wave represents an interesting aspect of the decarbonisation transition in the UK, and this research addresses that evolution through the lens of transition theory.

This thesis critically evaluates the "seven functions" model of Technological Innovation Systems theory and is set out in ten chapters.

This first chapter sets the scene for the evaluation, discussing the socio-technical transition currently under way in the decarbonisation of the energy system.

Chapter 2 reviews the relevant literature in the field of transition theory, focussing on the Multi-Level Perspective and Technological Innovation Systems approaches. It finds that these approaches are not well integrated, and that a "seven functions" model is presented without empirical support for the existence or importance of the seven functions. This leads to the core research question: "Does the 'seven functions' model in TIS provide a necessary and sufficient framework for characterising the emergence of new technologies, with specific reference to offshore wind and marine renewables in the UK?"

Chapter 3 sets out the research philosophy and methodology. It recognises that the core research question comprises two parts: the question of necessity of the seven functions and the question of their sufficiency. Accordingly, it adopts appropriate philosophical and methodological approaches to address these separate questions and defines the research methodology. The approach to recruiting interviewees, undertaking and analysing the research interviews is described.

Chapter 4 reviews the literature on functions in TIS to develop a long list of those functions which have been proposed over time, and then applies a list reduction and grouping approach to produce a refined list of functions to be examined in this work.

Chapter 5 addresses the question of necessity of the functions. It is split into seven parallel streams, as it analyses the research interviews to consider each of the seven functions in turn, before combining this analysis to explore the relationships between the seven functions.

Chapter 6 considers the sufficiency of the functions and reviews the interview data to find that a common theme emerges which allows the identification of an eighth function.

Chapter 7 defines this proposed eighth function - "relative value potential" – and justifies the decision to characterise the new function as a new function rather than within an existing function. It uses the interview findings to describe it in terms of the functional attributes of actors, institutions and networks, and metrics used for functions in Chapter 5.

Chapter 8 explores potential measures for the new function. It reviews existing technological and economic measures and proposes a new metric – Full Cost of Energy, or FCOE. FCOE attempts to incorporate externalities into the existing LCOE formula. The chapter then tests this new metric for offshore wind against an appropriate counterfactual of CCGT.

Chapter 9 is a wider discussion on the collateral findings of this research. It explores whether there appears to be scope for reconciliation of TIS and MLP, and what lessons might be learned by the marine renewables sector from the emergence of offshore wind.

Finally Chapter 10 concludes by reviewing the research questions and setting out how this research has addressed them. It describes the contribution of this research to the literature, its potential weaknesses of this research and identifies some areas in which this research might be extended, refined and applied.

Figure 1-5 shows the thesis structure in graphical form.

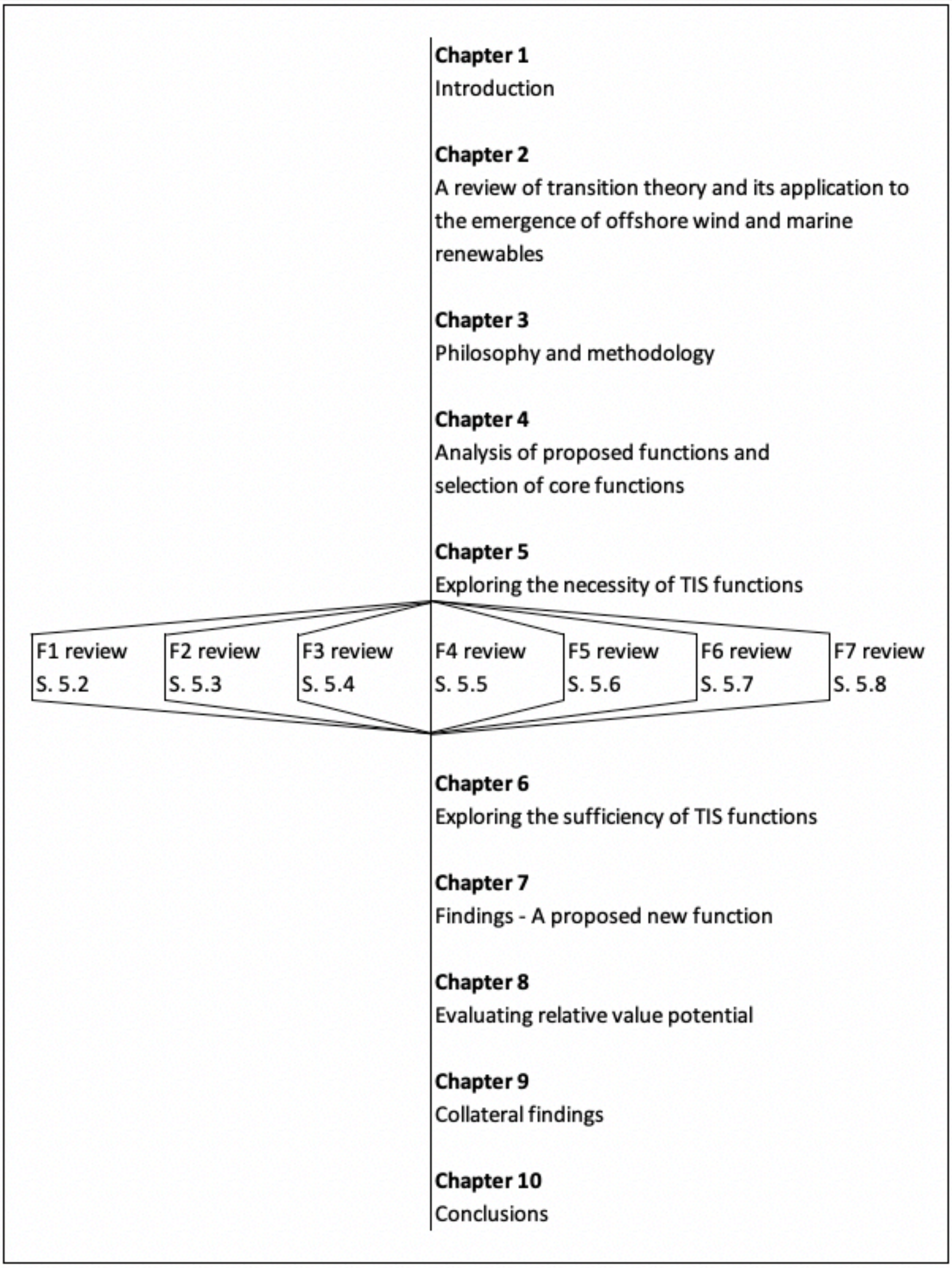

Figure 1-5: Thesis structure

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2 A review of transition theory and its application to the emergence of offshore wind and marine renewables

The emergence of offshore wind as an important contributor to the UK energy mix has been a significant transition in the UK energy system. Tidal stream and wave technologies may also emerge in time. This research explores these evolutions through the lens of transition theory, with the aim of testing an aspect of this theory and learning about the actual wind transition and the potential emergence of wave and tidal.

This chapter considers the literature on Transition Theory and its application to this research area. It is divided into 8 sections. Section 2.1 briefly describes the socio-technical system under consideration in this research. Section 2.2 provides an overview of the broad field of transition theory, and very briefly describes the 4 leading current research strands. Section 2.3 provides a review of Technological Innovation Systems ("TIS") theory; Section 2.4 provides a similar review of the Multi-Level Perspective ("MLP"). Section 2.5 compares TIS and MLP, and identifies areas of convergence and difference before Section 2.6 considers a proposal for integration of the frameworks. Section 2.7 identifies two areas of weakness in TIS, specifically identifying questions of empirical support for the functions used and reconciliation with the MLP approach, and Section 2.8 concludes with the research objectives and questions emerging from this review.

2.1 The socio-technical system

Before discussing theoretical frameworks, it is important to define the socio-technical system under consideration in the research.

The research addresses the emergence of marine renewables, comprising offshore wind, tidal stream and wave energy, as part of the UK electricity generation system. This system is centred on the electricity generators (dominated by the "Big Six" of BG, EdF, Eon, RWE, Scottish Power and SSE), their customers, supply chain, regulators and all of the formal and informal rules (often called institutions in the transition theory research) which govern how those actors interact.

It also includes those actors and associated institutions concerned with developing offshore wind, including technology and project developers, relevant regulators and other stakeholders.

Finally, the time scale with which the research is concerned has been defined as the period from 2000 to the present. The socio-technical system is defined in more detail in Section 3.6.

2.2 Introduction to transition theory

Technological transitions have been defined as major technological transformations in the way societal functions are fulfilled [82]. There is a huge literature in this field: a recent paper by Sovacool and Hess [83] exploring conceptual frameworks useful in explaining socio-technical change identified "96 theories and conceptual approaches spanning 22 identified disciplines."

This research relies on Markard et al.'s [84] typology of "major contributions and core research strands in the field of sustainability transition studies" to begin to home in on theoretical frameworks within transition theory.

Figure 2-1 from Markard et al. [84] applies a typology to key academic papers in the field of transition theory over the past four decades, and identifies four principal current research strands.

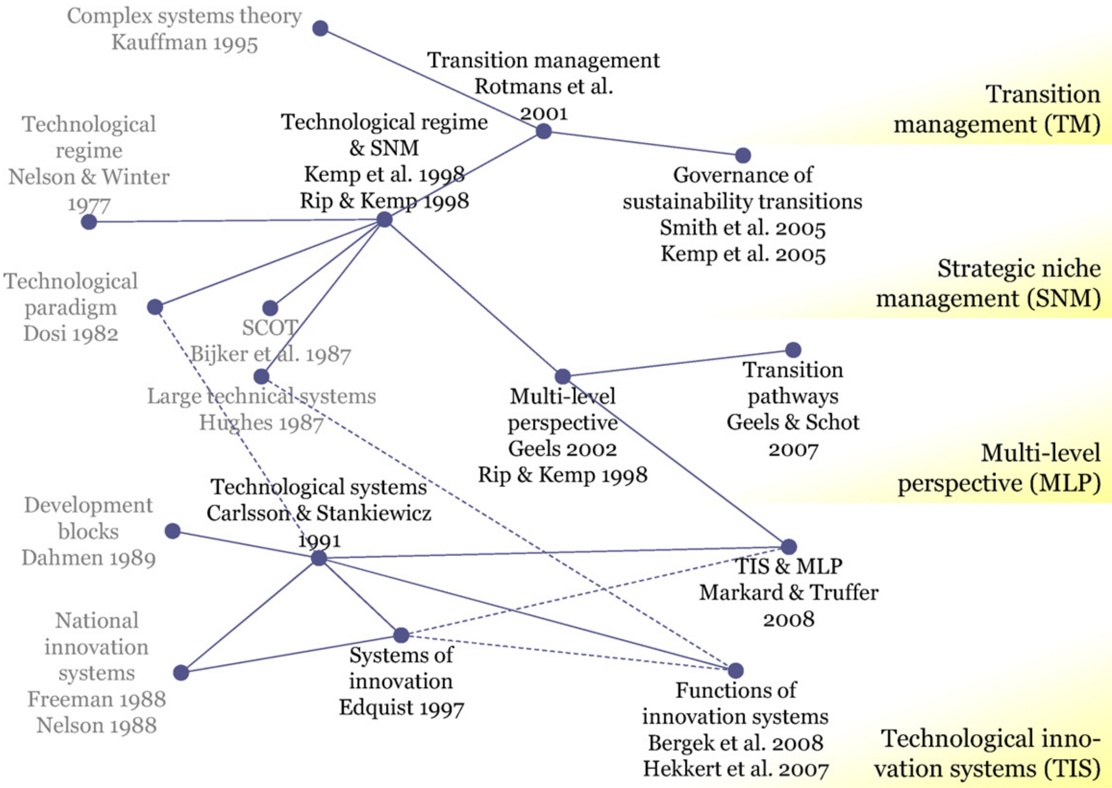

Figure 2-1: From Markard et al., (2012)

While Markard et al.'s [84] typology identifies four current "research strands" (TM, SNM, MLP, TIS) within the field of transition theory, a review of the literature suggests that in practice there are two principal camps among researchers in this area: Technological Innovation Systems (TIS), and Socio-Technical Transition Theory incorporating a Multi-Level Perspective (MLP). In limiting consideration of theoretical frameworks to TIS and MLP, it is necessary to explain the rejection of SNM and TM.

2.2.1 Strategic Niche Management

Strategic Niche Management (SNM), originally proposed by Kemp et al. [85], considers the policies through which evolutions of technologies from "niche" to "regime" level may be achieved and encouraged and is clearly congruent with the Multi-Level Perspective. As such, it is considered to be part of the MLP approach and is therefore not considered to be a separate field for the purpose of this research. SNM will provide insights in the policy aspects of the niche to regime evolution.

2.2.2 Transition Management

Markard et al. explain that Transition Management (TM) aims to guide policy-making and offers a "practice-oriented model for influencing ongoing transitions" [84]. They describe how TM focuses how policy-based interventions can be made to influence transitions, and explain that TM provides "an instrumental, practice-oriented model for influencing ongoing transitions". They go on to suggest that the approach has yet to demonstrate impact, referring to Kern and Smith [86] with the comment "Given recent drawbacks in actual policy contexts, the role of transition management and of related evolutionary approaches in national policy-making processes remains to be seen.

Kern and Smith [86] analysed the Energy Transition Project undertaken by the Dutch Government in the early years of the decade. The project was "based upon a 'TM' model aimed at achieving a sustainable energy system in the Netherlands by 2030." Kern and Smith found that while "the policy model seems innovative", "the merits in practice are unclear". In detail their concerns were that the "transitions approach risks capture by the incumbent energy regime". Such a capture would allow incumbent actors to influence the transitional trajectory to their benefit, and to slow or block any substantive change to the socio-technical system, and also to impede niche development.

With its principal focus on policy making, particularly at the national level, TM is considered not to offer an over-arching explicative framework required by this study and has therefore been excluded as a theoretical framework.

2.2.3 Focus on TIS and MLP

Having recognised that SNM is included within MLP, and ruled out a TM approach for this research, an assessment of TIS and MLP is required. The relative features, strengths and weaknesses of TIS and MLP are explored in Sections 2.3 and 2.4.

2.3 TIS – Review

2.3.1 Overview

Innovation systems theory offers a range of analytical frameworks within which the processes of innovation can be considered. The Technological Innovation

Systems approach is a special case developed over the past two decades, within which technology defines the unit of analysis (rather than, say, the innovation being defined in national or sectoral terms).

Carlsson and Stankiewicz [87]] defined technological systems as "dynamic networks of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilisation of technology" and recognised that studying the inter-relationships between innovation at the scale of the firm and the broader economy can help to understand economic growth at a macro level. While their focus was on understanding macro-economic growth, rather than on sub-systems within the wider economy, the consideration of the social and economic context in which innovation takes place seems equally useful in considering innovation within economic sub-systems.

Carlsson and Stankiewicz defined five elements in a technological system: economic competence, clustering, networks, development blocks and institutional infrastructure.

- **Economic competence** is "the ability (of actors) to develop and exploit new business opportunities".

- **Clustering** facilitates innovation by creating economies of scale and concentrations of labour skills and nucleating supply chains.

- **Networks**, whose "essential function is the exchange of information", and which can include entrepreneurs, academics, and supply chain participants, as well as primary actors in the technological system.

- **Development blocks**, as defined by Dahmen [88] and adopted by Carlsson and Stankiewicz, comprise the factors which allow technological development, and can include price and cost signals, and the creation of new markets and new manufacturing techniques and products.

- **The institutional infrastructure** within which the technological system operates, comprises both the formal infrastructure (such as economic institutions and capital markets, the role of government and public policy) and informal (production and distribution of knowledge).

In 2002, Carlsson et al. [89] considered some "analytical and methodological issues arising from various system concepts", in an attempt to answer questions of how to operationalise the theoretical framework. The questions they asked were (i) what is the appropriate level of analysis? – recognising that the specific research question influenced the appropriate "choice of components and system boundaries", (ii) how should the boundaries of the system under consideration be defined?, and (iii) how to measure the performance of the system?

In summary, they concluded that while definition of the level of analysis and definition of the components of the technological innovation system to be studied were tractable questions, further work was required to address the question of performance measurement.

Bergek et al. [90] later further defined a technological innovation system as "a set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field", focussing the Carlsson and Stankiewicz definition onto the area of innovation.

In summary, at a recent conference it was stated that the Technological Innovation System approach considers the roles of actors relevant to a technology innovation, their networks and the "role of institutional arrangements in the promotion or hindering of innovations" [91].

2.3.2 Key features of a TIS

The TIS literature describes the key features of an innovation system as actors, networks, institutions, technologies and regions.

2.3.2.1 Actors

Actors are described by Bergek [92] as "firms along the whole value chain, universities and research institutes, but also public bodies, industry associations and relevant non-commercial organizations, venture capitalists, organizations deciding on standards". Other sources of funding, such as grant providers, third party funders and other bodies with an interest in and influence on the sector under consideration are also considered in this function by function review. Bergek suggests identifying actors by sampling industry associations, searching patents and bibliometrics analysis, together with interviews and discussions with technology experts. This last approach has contributed the identification of actors in this research, with a "snowball sampling" approach [93] taken to identifying relevant interviewees.

2.3.2.2 Networks

Networks are described by Bergek [92] as comprising both formal and informal constructs. Bergek suggests that formal networks may arise in bodies "orchestrated to solve a specific task, such as standardization networks, technology platform consortia, public–private partnerships or supplier groups having a common customer". Informal networks can include "buyer-seller relationships and university/industry links". These networks have been identified through the interviews in this research, and their effects (both enabling and limiting) on the emergence of the technology have been considered.

2.3.2.3 Institutions

Institutions are described by Bergek [92] as "culture, norms, laws, regulations and routines" which bear on the emergence of the technology in question. These institutions have also been identified through the interviews and their effects considered.

2.3.2.4 Technologies and regions

Technologies and Regions, as described by Darmani et al. [94], have not been employed as headings in this review, as the scope explicitly defines the technologies under consideration as offshore wind, tidal stream and wave power (together, offshore renewable energy) and the region as the United Kingdom.

2.3.3 The introduction of "functions"

Bergek et al. [92] then sought to address Carlsson et al.'s [89] question on measurement, by introducing the "functions" approach, in which the degree and success of technological innovation is assessed through seven functions. They defined these functions as follows:

- Entrepreneurial activities – the level of activity by entrepreneurs in relation to the technological transition under consideration
- Knowledge development – the creation of technical knowledge through research and development, including patents, prototypes etc.
- Knowledge diffusion through networks – the sharing of knowledge between actors, including entrepreneurs, academics, government
- Guidance of the search – pressure from influencers that guides innovation in a preferred direction
- Market formation – mechanisms which support continuing innovation for a technology which is uneconomic but is worthy of development
- Resources mobilization – the activation of people, finance and physical resources (such as development sites) which enables the innovation
- Creation of legitimacy/counteract resistance to change – the enabling of innovation by making it legitimate (both legally and within a social context)

The functional definitions were refined by Hekkert et al. [95] and are discussed in more detail in chapter 4.

2.3.4 Metrics, drivers and indicators

Researchers seeking to operationalise TISs have developed a number of ways of describing the relative completion of various aspects of a technology's emergence. Some have worked within the "functions" framework and developed "metrics" and "indicators" to assess emergence.

Both metrics and indicators allow for assessment of functional performance. There is no clear division between metrics and indicators, although metrics tend to be more quantitative measures of functional performance, while indicators are more often qualitative demonstrations of support for the emerging TIS [96].

For example, Hannon et al. [97], in their report on the effectiveness of wave energy innovation policy in the UK, developed metrics for each of the Hekkert functions. Similarly, Miremadi et al. [96] proposed a comprehensive set of "indicators"; both of these offered quantitative measures of the completion of each of the seven functions proposed by Hekkert at al.

Darmani et al. [94] took a slightly different approach and proposed a typology for "drivers" for renewable energy technologies. They defined drivers as the "factors that foster" and as "the processes that influence trends and our ability to meet agreed-upon targets" and organised their drivers according to the conventional and widely-used organisational TIS headings of Actors, Institutions, Networks, and included the additional headings of Technology and Region.

Drivers, as described by Darmani et al. [94], are further removed from things that can be directly measured. They focus on the enabling architecture affecting the TIS, and in their typology of drivers, Darmani et al. categorise them according to actors, institutions, networks, technologies and regions, rather than by function. That said, some examples of drivers, or "factors that foster" [94], can be tentatively mapped into one or more functions.

Some possible metrics, indicators and drivers, including examples taken from this research, as well as work by Hannon et al. [97], Hekkert et al. [95], Darmani et al. [94] and Miremadi et al. [96] are set out in Table 2-1.

Function	Metrics	Indicators	Drivers
F1- entrepreneurial activities	Numbers of participants Number of technology experiments Numbers of startups	Technology convergence Maturity of technology Entrepreneurial culture Availability of venture capital	Engagement in demonstration projects Acquisition of relevant companies
F2 – knowledge development	R&D projects Patents Investments in R&D	R&D strategies Scientific publishing Learning rates	Effort on technology development

F3 – knowledge diffusion	Numbers of workshops and conferences Numbers of press articles	Network size and intensity Scenario / fore-sighting projects	Existence of societal networks
F4 – guidance of the search	Targets set by governments / funding bodies Numbers of articles in professional journals	Policy action plans Quality of academic and industry discussion Mapping specific government or industry targets	Policy support and effectiveness
F5 – market formation	Numbers of niche markets Specific tax regimes New environmental and other standards	Supportive regulatory regime Development of standards Public market support Incentives and subsidies	Willingness of retail customers to pay premium for "green"
F6 – resource mobilisation	Funds made available for R&D Funds for testing Numbers of workers in sector	Development of innovative financing ICT access Venture capital deals	Cooperation across supply chain
F7 - legitimation	Numbers of interest groups and members Lobby actions by interest groups	Lobby actions Regulatory acceptance IP protections Political consistency	Trust and risk tolerance

Table 2-1: Some examples of metrics, indicators and drivers (from Hannon et al. [97]*, Hekkert et al.* [95]*, Darmani et al.* [94]*, Miremadi et al.* [96] *and author's analysis)*

The characterisation of quantitative metrics and qualitative indicators, together with the identification of associated drivers are undoubtedly important in considering the development of a TIS. Accordingly, the analysis of the research interviews has addressed these matters, identifying where interviewees have raised or discussed potential metrics, indicators and drivers.

2.3.4.1 Operationalisation of the functions

In a recent report applying TIS to innovation policy for the emergent UK wave energy industry, Hannon et al. [97] operationalised these functions by developing and evaluating metrics for each. For example, knowledge development was assessed by considering the numbers of relevant patents in the area of wave energy, both in absolute terms and as a fraction of worldwide patenting activity. This operational approach, although clearly susceptible to criticisms that patent numbers need not directly correlate with innovation success, has provided insights into the success of innovation policy in UK wave energy and demonstrates the applicability of the TIS framework.

2.3.5 Acknowledged weaknesses and development areas

While many researchers active in Technological Innovation Systems, from Carlsson and Stankiewicz [98] to Hannon et al. [97] have shown the applicability of the TIS framework in considering technological transitions, a recent debate chaired by Truffer [91] identified and sought to address recent criticisms of the approach.

Markard et al. [99] summarised these criticisms as follows, and sought to address them.

- **Context.** It is suggested that the TIS approach involves "a perceived myopia and lack of attention to context factors". Leading TIS research Anna Bergek and her colleagues admit: "At the same time, the functions framework does not give much explicit attention to the dynamics of surrounding contexts." [90].

- Hannon's recent work [97] demonstrates this lack of context: by assessing only the impact of innovation policy on the development of wave energy, he fails to account for exogenous factors (such as the rapidly falling cost of offshore wind over the period) or technological challenges (the technical difficulty of actually developing and deploying a wave energy device).

- In response, Markard et al. [99] propose that conceptual extensions of the TIS framework should be encouraged, specifically to address "context structures, their dynamics and interplay with focal TIS". In even more recent work, Markard [100] noted that in the case of novel technologies such as wind and photovoltaic that "not just the focal technology is emerging but also the specific organizations, institutions and networks that support this technology. In other words there is a co-development of the TIS and its underlying focal technology." He added that "changes in the TIS context can have an impact on the focal TIS. These changes may occur independent of the dynamics of the focal TIS, e.g. in the sense of "landscape-type developments".

- This extension of the TIS to consider contextual factors appears to bring the TIS approach closer to the Multi-Level Perspective, which specifically includes context factors (including features it describes as "landscape" and "regime lock-in"). Bergek et al. [90] address this weakness directly, by proposing the definitions of "external links" and "structural couplings" to provide a conceptualisation framework for contextual impact on a TIS.

- **Delineation of TIS.** It is suggested that TIS scholars can define the boundaries of the TIS "ad hoc and based on simple templates", thereby "missing out on important relationships or interactions".

In response, Markard et al. [99] emphasise that "TIS delineation must be done carefully". They go on to explain that delineation of the TIS should take account of three aspects: dimensionality - many several dimensions of the TIS under consideration, including breadth of technological field, how much of the value chain to include, where the best spatial delineation lies (ie local, regional, national or global) and what timescale is most appropriate; context – delineation of the TIS should take account of the research question being addressed; networks – any delineation will cut across network boundaries, where networks include actors, technologies and institutional structures. Care should be taken to ensure that the delineation cuts these at appropriate lines of cleavage. Finally, Markard et al. raise the ontological question of whether a TIS actually exists with an objective reality or is simply a "purely analytical construct". They suggest, and this author agrees, that a TIS is neither one nor the other, but has aspects of both. They suggest that as a concept it is similar to a firm, or perhaps more accurately, "an industry sector".

- **Spatial dimension.** Markard et al. [99] recognised that it is critical to define the geographic extent of the TIS clearly. They accepted the criticism that TIS analysis can overlook important features outside the spatial boundary defined for the study, if this spatial aspect is poorly defined. They refer to the example of solar photovoltaic (PV) technology, where very different aspects of technological innovation took place in geographically discrete areas.

In response, they point out that some TIS scholars have sought to address and unify these spatial aspects, and they urge practitioners to take account of spatial context.

- **Usefulness.** Markard et al. [99] say that the TIS approach is "viewed as a key framework in transition studies", although it was "not designed for this in the first place". They find that some scholars cast doubt on the usefulness of TIS analysis, claiming that it was developed as a tool to understand emerging technologies, and can fail to take account of "lock-in" and other pressures towards maintaining the status quo in socio-technical regimes. These criticisms appear to arise from advocates of the Multi-Level Perspective and generally seem to take the view that TIS and MLP are incompatible. Encouragingly, [101] has argued that the two approaches can complement one another and this author shares this view. Section 2.5 describes this potential integration.

In response, Markard et al. [99] admit that while TIS "cannot cover all aspects of socio-technical transitions", and specifically admit that it does not address "the decline of (incumbent) socio-technical systems, they aver that "it has the potential explain other processes in socio-technical transitions" and that it is worthwhile.

- **Incorporation of politics.** It is suggested that the incorporation of politics, which researchers adopting the MLP framework would consider landscape factors, is not always well addressed in TIS analysis.

Markard et al. [99] accept this critique, and urge TIS scholars to strive to take greater account of these factors.

- **Limits for policy recommendation.** Markard et al. [99] recognise that TIS often considers how policy contributes to the development of a technology, and does not specifically address the question of whether the development of the technology is in itself desirable. Hannon's report [97] follows this pattern precisely. It is implicit in its analysis is that the development of wave energy technology is desirable, although this question is not directly addressed. A variant of this critique is that TIS can lead to general policy recommendations, rather than specific proposals. This critique can be levelled equally at MLP, and is not necessarily a side effect of the use of TIS.
-

Markard et al. [99] note this critique, and encourage TIS scholars to maintain an objective distance from the questions they consider. They further note that the critique is not specific to use of TIS.

2.4 MLP – Review

2.4.1 Overview

Rip and Kemp [102] sought to understand technological transitions within a wider societal context, and focussed on technologies implicated in global climate change, either as a source of the problem or a possible solution. They set out to understand "the nature and dynamics of technical change; how technology is shaped by social, economic, and political forces alike; and how, in the same process, technologies and technology systems shape human relations and societies".

This holistic approach was developed by Geels, who introduced the Multi-Level Perspective as applied to socio-technical transitions [82]. This important paper set out a hierarchy of levels within a socio-technical system as shown in Figure 2-2.

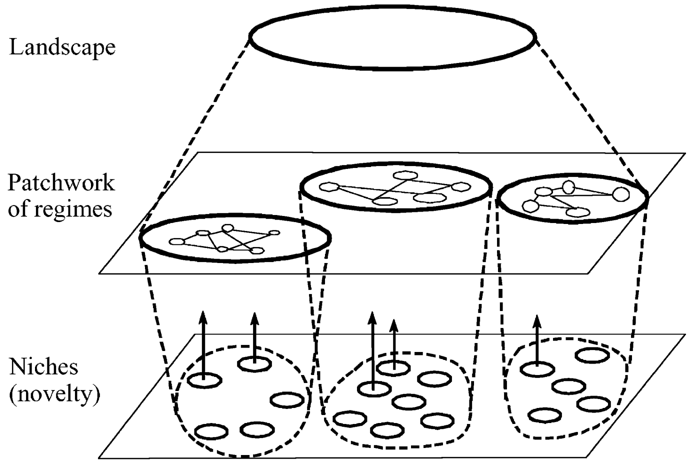

Figure 2-2: From Geels (2002)

The landscape level is "an external structure or context for interactions of actors" in which the societal context for the socio-technical regime is defined. It is subject to slow change and can be affected by changes within the regime or the niches to which it pertains. In the context of the introduction of offshore renewable energy to the UK energy mix, landscape factors would include social attitudes towards renewable energy and climate change and the political stance of the incumbent government and European Union towards climate change issues.

The regime level describes the incumbent socio-technical system, which in this study is defined as the UK electricity generation system as it stood in 2000. At this stage, the generators and transmitters of electricity had been privatised, some limited competition for customers was emerging, there was little pressure to change the system to lower-carbon sources of generation, and there was very little renewable power contributing to the system (primarily Scottish hydro projects built in the period from 1940-1960) [103].

The regime level comprises the actors who participate in the incumbent socio-technical system, including (in this case) power generators, regulators, technology providers and consumers. The regime typically acts to maintain the status quo, and can actively seek to stifle development of potentially challenge niche technologies. As Geels [82] put it, "regimes create stability because they guide the innovative activity towards incremental improvements".

The niche level describes the "safe spaces" where special circumstances permit the evolution of new technologies which can go on to challenge the regime "status quo", and through a process of transformation over time, redefine the regime. These special circumstances can include funding support (UK Government, EU funding), entrepreneurial activity (supportive "angels" funding technology development), or development of technology for other applications being found to be valid in the regime.

Each of the three "levels" – landscape, regime and niche – can influence the others as shown in Table 2-2 below.

	Landscape influenced by	**Regime influenced by**	**Niche influenced by**
Landscape influences	-	Changes to legal framework, regulatory regime, changes in societal attitudes drive regime performance	Societal support and legal framework (including EU) provides funding and legitimacy for niche activities
Regime influences	Actors in regime lobby landscape actors to maintain lock-in	-	Defines threshold for niche break-out, including economic and performance criteria
Niche influences	Niche demonstration of viability of technology and niche actor lobbying can influence landscape support	Emergence of niche technologies can influence adoption by regime actors; regime norms can change to include niche technologies	-

Table 2-2: Influences between levels in MLP (author's work)

2.4.2 Acknowledged weaknesses and development areas

A number of criticisms have been directed at MLP; Geels [104] has sought to address these. The issues identified, and rebuttals are summarised below:

- **Lack of agency.** As Geels [104] says, "the MLP has been criticized for underplaying the role of agency in transitions". Geels rebuts this, claiming that the MLP is "shot through with agency" because the trajectories that the MLP describes are "enacted by social groups". While this is obviously true, it does not address the underlying criticism that MLP fails to address the specifics of how actors achieve transitions. In more detailed comments, Geels points to other researchers who have sought to incorporate agency more explicitly within the MLP.

- **Operationalisation of regimes.** Geels [104] states that "several criticisms concern the operationalisation and specification of systems". Geels points out that the problem of system definition, or defining boundaries, is a general criticism applicable to virtually any field of analysis, and it is noted that a similar criticism has also been levelled at TIS. Geels accepts that multi-regime studies, in which the interplay between regimes also has an effect on transitions would be "a promising topic". It is perhaps significant that Geels does not address the criticisms in relation to operationalisation of the MLP – the literature offers little in the area of operationalising the MLP.

- **Bias towards bottom-up change models.** It is suggested that the MLP has been "criticised for a bias towards bottom-up change models". While Geels [104] accepts that early MLP work "emphasized bottom-up dynamics", he goes on to rebut the claim by referring to his own work [105] on the typology of transitions and the relationship to landscape changes. There is little attempt in his work to operationalise the derivation of transition typologies.
- **Heuristics, epistemology and explanatory style.** Geels [104] refers to the suggestion by Genus and Coles [106] that the "potential contribution of the MLP/transitions framework could be limited to

offering a heuristic device”. Geels accepts that this would be a powerful criticism in a positivist research tradition, but rebuts it, saying “heuristics are seen as important in interpretive traditions”. In essence, Geels denies the criticism by saying that it comes from a different research tradition than the tradition in which he considers MLP as operating. This might offer a route to new work, where if one is to use the MLP in a positivist paradigm, it would require attention to ensure that its findings had explanatory and predictive value, rather than being simply descriptive.

- **Methodology.** The MLP is frequently based on case study, which Genus and Coles [106] suggest allows the “flawed use of secondary data sources” and the use of “uncritically accepted” accounts. Geels [104] again notes that this criticism could be valid in relation to his own work, and further accepts that MLP case studies have been aimed at illustration and exploration, rather than systematic research. Again, this is an implicit retreat to the interpretivist tradition, when Genus and Coles [106] appear to be setting the more objective standards of the positivist approach.

- **Socio-technical landscape as a residual category and flat ontologies versus hierarchical levels.** The final criticism addressed by Geels [104] is that the landscape level, as defined in the Multi-Level Perspective, is a “’garbage can’ concept that accounts for many kinds of contextual influence”. Geels accepts this as a fair criticism and suggests that further theorization around the landscape level is required. The criticism that the landscape, regime and niches reflect ‘levels’ in a hierarchy is a misunderstanding of the MLP – they are simply different aspects of an overall socio-technical system, and Geels [104] makes this clear.

2.5 Cross-comparison

It is clear that both approaches, TIS and MLP, have much to offer in understanding transitions in socio-technological systems. The literature criticising TIS and MLP (e.g. [99,104]) appears to exhibit a tension between the TIS school and the MLP school, where researchers working in each framework will level criticisms, rather than finding areas where the frameworks to complement one another to developer richer and more textured understandings of technological transitions.

This research sees scope for a non-zero-sum outcome, in which each of these approaches can strengthen and contextualise the other. In seeking to develop this collaborative model, it is illuminating to consider how TIS operates from an MLP perspective and vice versa, as in reality each approach is considering the same broad process, from slightly different starting points.

It is clear that neither the MLP nor the TIS approach fully considers factors at work in a socio-technical transition. TIS appears to focus on the processes of innovation while MLP describes the large scale architecture of a transition

Table 2-3 shows the principal criticisms aimed at each of the approaches, and how this integrative framework aims to address them.

Criticisms of TIS	**Summary of criticism**	**How criticism might be addressed**
Context	TIS can fail to take account of context	Adoption of MLP landscape / regime / niche model builds in context
Delineation	TIS can poorly delineate system boundaries	The innovation system under consideration focusses on the large-scale (grid connected) power generation system of the UK, from 2000 until the present day. Despite clear system definition, it is accepted that some technological innovation will enter the system from outside UK
Spatial aspects	TIS can overlook important features outside spatial boundary	System boundaries permeable to innovation from outside UK
Usefulness	TIS has excessive focus on emerging technologies and can fail to take account of lock-in	Adoption of MLP approach includes explicit consideration of lock-in and other regime factors

Incorporation of politics	TIS can fail to take account of politics and other wider factors	Adoption of MLP approach includes explicit consideration of political and other landscape factors
Limits for policy recommendation	TIS limited to policy recommendations, founded on assumption that technological innovation is desirable	MLP explicitly considers lock-in of regime and allows for assessment of innovation desirability.
Criticisms of MLP	**Summary of criticism**	**How criticism is to be addressed**
Lack of agency	Can underplay role of agency	Use of TIS functions approach allows for clear identification of agency effects
Operationalisation of regimes	Operationalisation of MLP is not well described	TIS functions allow for evaluation of niche-regime dynamics
Bias towards bottom-up change models	Early MLP focussed on "bottom-up", but more recent work on typology of transitions has begun to address this	TIS functions allow for mechanics of transition to be better understood
Heuristics, epistemology and explanatory style	It is suggested that the MLP is "limited to offering a heuristic device"	Application of functions approach provides specific and quantifiable assessment of transition
Methodology	Case study basis can allow for "uncritical" use of secondary data	This study aims to use objective data where possible, although it is recognised that some more qualitative information will make the analysis richer
Landscape as a residual category	It is suggested that the landscape can be used as a 'garbage can' for factors not captured within the regime or niche	This study aims to define the system such that the landscape comprises those aspects of the system over which regime and niche participants have no direct control, but which nonetheless relate to the system (e.g. EU Climate Change directives, changing public attitudes to renewables)

Table 2-3: How an integrated approach could address TIS and MLP criticisms (author's work)

In MLP terms, the TIS approach focusses on the process by which "niche" technologies can become part of the "regime" and takes some account of the "landscape" through its consideration of institutional infrastructure (which is defined widely). TIS does not specifically take into account the processes of regime destabilisation, or the importance of changes in the landscape on the potential for technologies to break out of niches into the regime.

TIS can be used to focus on single aspects of technological innovation, such as innovation policy. Such a focus can lead to undue weight being attributed to single aspects of the technological transition process. As an example, Hannon's [97] focus on innovation policy concludes that the failures and weaknesses of innovation policy were a significant factor in the failure of wave energy technologies to achieve commercial success. Other factors, such as the engineering difficulties represented by the technological challenge, the competitive environment in which offshore wind was rapidly reducing its own costs and the failure of some businesses in the sector also had a significant bearing but were not included in Hannon's scope.

Equally, the MLP approach does not address some factors considered important by the TIS approach. As a result, it is weaker on the specifics of how the transition from niche to regime can occur. Considering Carlsson's [98] five elements in turn:

- **Economic competence:** the ability of actors to take advantage of innovation is not directly addressed by the MLP. MLP tends to focus more on the processes of innovation, rather than the actors who do it. This was recognised by Geels [104], as a weakness in how MLP addressed the importance of agency.
- **Clustering:** the MLP approach does not directly address the value of clustering
- **Networks:** the MLP approach does not specifically consider the importance of networks
- **Development blocks:** the concept of development blocks is contained with the landscape and also as a factor which can lead to regime destabilisation
- **Institutional infrastructure:** this is described both within the "landscape" and also within the political, economic, social, technological, legal and environmental analysis of the regime

The MLP does not clearly address the question of the precise mechanism by which niche technologies “break out” and become part of the regime, and in this area some further work is required.

Practitioners should seek to avoid applying positivist criticisms to an interpretivist approach, or vice versa, as this foundational mismatch is unlikely to yield helpful results and may reinforce apparent schisms between practitioners from different traditions.

2.6 Integration of frameworks

2.6.1 Markard and Truffer’s proposal

The previous sections show that while TIS and MLP attempt to understand broadly similar processes and events, they apply different frameworks and often come from different philosophical starting points.

Markard and Truffer [101] note that both the innovation systems approach and technological transitions approach are rooted in evolutionary economic theory and recognise that both approaches “highlight the importance of networks and learning processes”. They further add that “scholars in both fields usually apply an interdisciplinary perspective and account for the particularities of spatial and historical contexts".

They propose an integration of the two approaches, with “a concept of technological innovation systems that allows integrating the multi-level framework and the innovation systems concept for the study of emerging, far-reaching novelties”. Their proposal defines a Technological Innovation System “in a narrower way than existing system concepts” and includes a preliminary set of minimum criteria an empirical field has to fulfil so that the application of the TIS concept makes sense”.

Markard and Truffer [101] state that “the innovation systems approach and the multi-level framework represent different perspectives on processes of innovation and socio-technical transformation”. In integrating the frameworks, it seems clear that a reconciliation of philosophical frameworks (or at least agreement on which one to adopt) is a desirable starting point.

While they do not attempt to develop a combined framework, as this would be "an endeavour that exceeds the limits of the current paper", they do "summarize a number of conceptual issues a combined framework should strive to address".

They suggest that "a combined framework should clarify the relevance, need and application domain of each of its conceptual elements". They further state that a framework, by which they mean a generalised theoretically-driven structure, should "be applicable to different kinds of innovations and it should capture innovation dynamics at different levels". They add that any combined approach would be most useful if it addressed the key shortcomings of the frameworks previously identified, which they summarised as follows:

- **Innovation processes:** more explicit consideration of innovation processes, especially considering issues of strategy and agency
- **Interdependencies between actors and institutions:** mutual interdependencies between actors and institutions
- **Consistent performance comparisons:** to identify and quantify success of innovations and innovation support
- **Systematic identification of all factors influencing innovation**: systemic identification and assessment of broad range of factors (events, developments, institutional effects, actor behaviour, etc)

Their integration of TIS and MLP accommodates the cross cutting of Innovation Systems (whether sectoral or technological) between a "patchwork of regimes" and identifies that both Technological Systems and Sectoral Systems of Innovation include elements which MLP would consider as being in the niche and regime layers. Their concern is that the definition of an innovation system can "creep", especially in areas where radical innovations are developed outwith the scope of the existing system (or regime, in MLP terms).

One specific weakness of Markard and Truffer's [101] proposed integration is that it proposes to define the system as it restricts the system to "only those actors, institutions and networks that are supportive to the innovation process". Furthermore, it proposes concentrating "on the innovation function", rather than contemplating the full system, including aspects which can make innovation fail. With these conditions, it is not clear how this proposed integration incorporates some of the real strengths of the Multi-Level Perspective, which specifically considers how the regime can maintain "lock-in" and resist niche break-out, and how wider landscape factors may enable niche break-out or regime destabilisation. It might be thought that their integration approach draws very heavily from the TIS tradition, and in practice accommodates little of the value that the Multi-Level Perspective can bring.

Accordingly, it is not proposed to adopt Markard and Truffer's [101] proposed integration of the two approaches.

2.7 Weaknesses in TIS

As a result of this review of the literature, the following apparent weaknesses in Technological Innovation Systems theory, and specifically its operationalisation through the 'seven functions' approach, were identified.

Foremost among these was the seven functions model itself. The literature presents multiple possible inventories of functions, without seeking to establish whether these inventories provide a necessary and sufficient framework to characterise a transition or validating these functions with the stakeholders for whom they are an everyday concern.

Additionally, while both the MLP and TIS approaches clearly provide illustrative frameworks for considering socio-technical transitions, they appear to form two opposing schools. This leads to a question of whether these two schools can be at least partially reconciled through modifications to the TIS functions approach.

2.8 The application of TIS to offshore renewables

The emergence of offshore renewables, most notably offshore wind, has been an important aspect of the evolution of the UK energy system over the last 20 years [65].

Although a number of the available transition theory approaches have been applied in this area (e.g. life cycle models [107], the multi-level perspective [108], policy and policy network-based [109,110] and whole systems modelling [111]), applications of TIS are scarce and limited in scope.

In the wind sector, Rui et al. [112] operationalised the "seven functions" model in relation to wind energy development in China (both onshore and offshore) by developing indicators to assess the degree of completion of each function. This "enables a more rigorous comparative analysis of energy innovation between countries", in which they found that China has begun to take a lead in R&D and innovation relative to "global market leaders" in wind energy – specifically Denmark, Germany and the USA – but still lags in "output and outcome indicators" such as numbers of patents and exports. Rui et al.'s framework

Jacobsson and Karltorp [113] considered the requirement for offshore wind capacity in Europe by 2050 and applied TIS to identify obstacles to this deployment. They used an existing functions inventory and attempted to measure the "strength" of each function (i.e. the degree to which each function had been completed) with their own qualitative metrics including "patent data reflecting 'knowledge development/diffusion'; statements regarding the desirability of wind power by politicians reflecting 'legitimation'; details of regulatory frameworks as indicators of 'influence on the direction of search' and 'market formation' and the number of firms (e.g. turbine suppliers, utilities) who diversify into offshore wind power and the uncertainties they choose to tackle (e.g. developing new turbine models or investing farshore) as indicator of 'entrepreneurial experimentation'".

Wieczorek et al. [114,115] applied a similar approach to Jacobsson and Karltorp, and compared the relative performance by function of the offshore wind TIS across Denmark, the UK, the Netherlands and Germany to identify potential blockages to large scale offshore wind development.

The work of Jacobsson and Karltorp and Wieczorek et al. clearly confirmed the potential for the TIS seven functions model to be operationalised in offshore wind, although formal metrics were not developed and there remained a qualitative dimension to the assessments. However, these researchers did not seek to validate the functions inventories they used, nor to seek actors' views on the perceived importance of each of these functions. In contrast, they implicitly assume that the functions inventory is complete (both necessary and sufficient) and therefore that scoring well on all of these functions would necessarily lead to significant deployment of offshore wind in Europe.

In wave energy, as discussed in Section 2.3.4.1, Hannon et al. [97] undertook a review of wave energy innovation policy through the lens of TIS. They adopted Hekkert's functions and considered the effectiveness of wave energy innovation policy through this lens, without apparently considering whether the functions inventory they used was necessary or sufficient to characterise the performance of the TIS. This approach, although clearly susceptible to criticisms, provided insights into the success of innovation policy in UK wave energy and demonstrated the applicability of the TIS framework.

Finally, it is also noting that Hekkert and Negro [116] undertook work in the biomass sector which was thematically close to the work undertaken in this research. They tested "whether the functions of innovation systems framework is a valid framework to analyse processes of technological change" and concluded that the framework was valid, although their methodology involved review of case studies, rather than direct discussions with actors in the sectors as to their views on the proposed functions framework.

2.9 Key issues arising from literature review

The literature review identified a number of key issues, which influenced the definition of research objectives and questions.

2.9.1 Functions definitions

The definitions of the functions developed by different researchers do not appear to be consistent, with each researcher developing their own functions inventory with limited reference to others. No evidence was found in the literature of any attempt to develop a comprehensive or authoritative functions inventory.

2.9.2 Functions validation

Researchers active in the development of functions did not appear to seek any external validation of their functions inventories, but simply developed their inventories from the work of other researchers or through their own thinking on the subject.

There are apparently close relationships between researchers in the area, as many papers are co-written between different combinations of the same authors. This may suggest that there has been little potential for external validation of these functions inventories.

2.9.3 Involvement of sector actors

As discussed in Sections 2.9.1 and 2.9.2, the development of functions inventories appears to have been undertaken by a limited group of researchers with little external validation.

No evidence was found in the literature for the involvement of sector actors – those individuals participating directly in the transition as project or technology developers, regulators or policy makers or supply chain participants.

2.9.4 Application to offshore renewables

The literature review found a small number of examples of the application of TIS, and specifically the seven functions model, to the evolution of offshore renewable energy in Europe.

While these examples confirmed the potential for TIS to be operationalised, their authors appeared to assume that the functions inventories they chose (all of which were closely based on Hekkert et al. [95] were complete and valid. The authors did not appear to seek actors’ views on the perceived importance of these functions, or whether these inventories were both necessary and sufficient.

2.9.5 Summary of key issues

In summary, the "functions" approach to TIS was recognised to offer a powerful and operationalizable framework within which to assess the emergence of offshore wind in the UK, and that research should seek to address these weaknesses.

2.10 Research objectives and questions

The aim of this research is therefore to evaluate the "seven functions" model of Technological Innovation Systems theory, to assess whether it provides a necessary and sufficient framework for explaining the emergence of offshore wind and marine renewables as part of the UK energy system and to see if there is potential for any reconciliation between the TIS and MLP approaches.

The objectives are:

- To identify any consensus characterisation of the seven functions model in the literature and refine it in the light of research findings
- To assess the perceived relative importance of the seven functions among stakeholders in the UK offshore renewable energy sector
- To assess the completeness ("sufficiency") and appropriateness ("necessity") of the seven functions model in describing the emergence of offshore wind, tidal stream and wave in the UK
- To identify, justify and define any additional functions emergent from this research
- To identify findings of relevance to the wave and tidal stream sectors from the specific findings on offshore wind
- To consider whether these findings offer any potential for reconciliation between the TIS and MLP approaches

Completion of these objectives will address the following research question: "does the 'seven functions' model of Technological Innovation Systems theory provide a necessary and sufficient characterisation of the emergence of offshore renewable energy in the UK?" This question is capable of being subdivided into a number of smaller questions which tie to the objectives above:

- Is there a consensus characterisation of the seven functions model?
- What is the perceived importance of each function in delivering the transition?
- Are the seven functions necessary and sufficient to describe the technological changes under consideration?
- If these functions are not sufficient, what other function(s) are required?

- How should any additional functions be characterised?
- What lessons are relevant to the emergent wave and tidal stream sectors from the offshore wind experience?
- Is there scope to reconcile or integrate TIS and MLP approaches? Specifically, can the functions approach from TIS elucidate the detailed process of niche break-out and be developed to include contextual insights from MLP?

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3 Philosophy and methodology

Having defined the research questions and objectives, this chapter considers the philosophies available with which to structure research, and the approaches and research methods that can be effectively combined to address the research questions set out in chapter 2.

This chapter is in 7 sections. Section 3.1 discusses the positionality of the researcher, which inevitably guided the research approach. Section 3.2 considers the philosophical paradigms applied in transitions research and selects an appropriate approach in the context of the research questions. Section 3.3 is a bridge from philosophy to methodology, and considers the application of inductive and deductive approaches to the research questions.

Section 3.4 then justifies the philosophical framework and identifies the preferred research strategy. Section 3.5 sets out the methodology in some detail, describing the process of interview selection, execution and analysis, before Section 3.6 defines the specific socio-technical transition considered in this research and Section 3.7 notes the methodological novelty of this research.

3.1 Positionality

Having discussed the literature, and developed the research question in Chapter 2, it is important to describe the positionality of the researcher. As defined by Qin [117], "positionality is the practice of a researcher delineating his or her own position in relation to the study, with the implication that this position may influence aspects of the study, such as the data collected or the way in which it is interpreted". In social research of this kind, where the measurement instrument is human, it is important to understand the background of the researcher as this influences the philosophical and methodological approach taken in this research.

This section is necessarily written in the first person, as it comprises a brief biography of the researcher and explanation of how this research came about.

I started my career as an oil industry geologist with a degree in Geological Sciences from the University of Cambridge. Almost immediately on beginning this stage of my career, I found that I was more interested in the business aspects of the work than the geology. That inspired me to undertake an MBA, to enable me to move from the technical disciplines to more commercial roles.

On completion of the MBA, I moved to work in Investment Banking for a period, gaining high level exposure to energy industry decision makers. Having found that my values and those of investment banking were not aligned, I rejoined the oil industry in a role which combined commercial, economic and strategic elements. This in turn led to a senior role in Texaco in the UK, as Finance Director for its North Sea Producing Business Unit.

In 2001, when Chevron acquired Texaco, I took an opportunity to take a redundancy package, and to start a renewables consulting business, finding that my experience from 15 years in oil and gas was transferable to the emerging renewables sector. I had been interested in renewable energy since my school days and the topic came up in my Cambridge admission interview as I expressed an interest in it in my application – and I was keen to make a living in this area.

Since 2001, my business – Redfield Consulting – has been operating in the renewables sector, with much of the work focussed on tidal stream, wave and offshore wind. I was a director of the European Marine Energy Centre in its early years from 2003 to 2009 (and still carry a torch for marine renewables), and also worked with the Beatrice offshore wind demonstrator project, and with the offshore wind developer that emerged from that project – SeaEnergy plc.

This accrued professional experience has given me a strong reputation and a broad and high quality professional network across the renewables space, and my attendance at conferences has allowed me to make further contacts as required. In considering the research question, it was clear that my network was a unique research resource. Accordingly, it seemed natural to make best use of this as a basis for the research.

My interest in energy, and particularly non-fossil fuel sources of energy long pre-dates this research. Even at school in the 1970s, I won a prize for an essay entitled "Is there an energy crisis?" [118]. Although this very early work suggested that nuclear power was a solution, my professional interest soon turned to renewable energy. More recently, my professional experience has led me to seek to understand the relative success of the emergence of offshore wind as compared with wave and tidal. Specifically, having been a director of EMEC and seen early development in the wave and tidal sector, and also having seen early offshore wind development work at Beatrice, I was intrigued by the question of what had led to the successful emergence of the latter technology, but not the former. As I had reached a stage in my career where I was able to pursue (and fund) a PhD whilst still also working in the field, I felt the time was right to formalise enquiries that had been in my mind for many years.

Although I sought to remain objective in this research, it is possible that my views as a strong supporter of renewable energy may have bled through into the findings; I do not believe that this is the case.

3.2 Research philosophies

The literature review in Chapter 2 found that different researchers operated within different philosophical paradigms. This section summarises the key aspects of a number of philosophical approaches as described by Saunders et al. [119](p107ff) and characterised as the outer layer in their "research onion" (Figure 3-1).

They set out four philosophies: positivism, realism, interpretivism and pragmatism which may be applicable in business research.

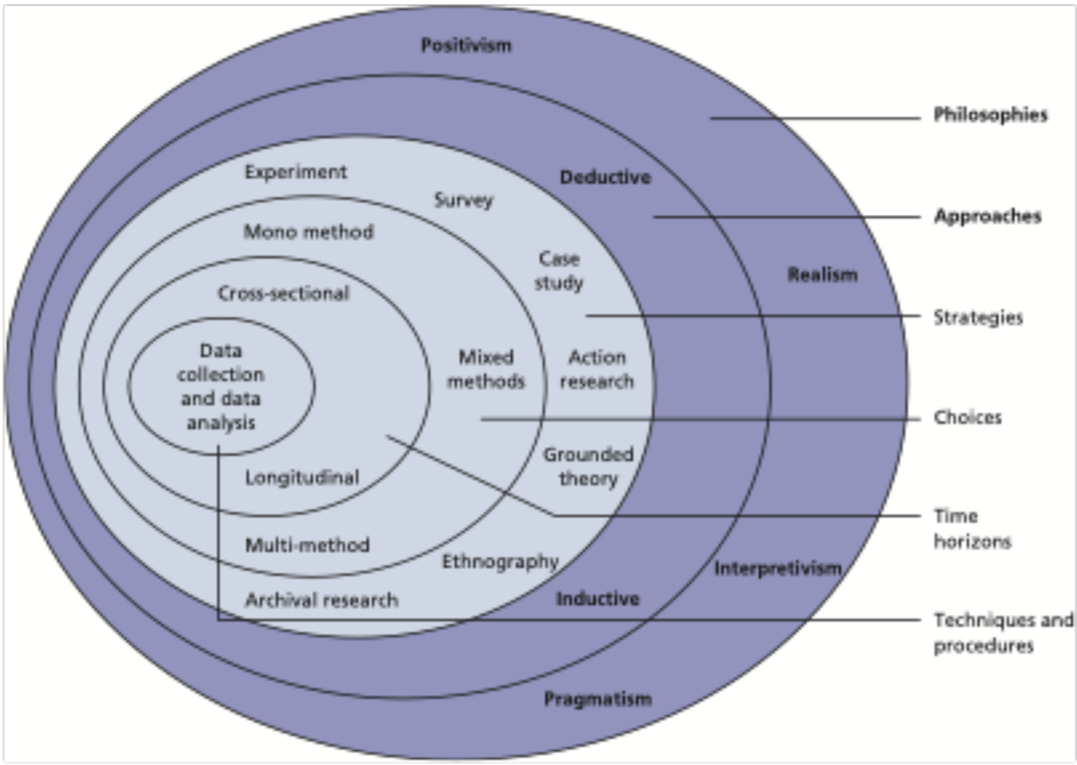

Figure 3-1: The research "onion" [119]

3.2.1 Positivism

Positivism, as described by Saunders et al. [119], limits research to questions which will "lead to the production of credible data". They clearly subscribe to the view that the "end product of such research can be law-like generalisations".

Positivism considers that the only authentic knowledge is scientific knowledge, by which it means knowledge derived through the scientific method, involving the definition and testing of hypotheses, and derivation of objective data and repeatable results.

Positivist research is undertaken in a "value-free" way, as far as is possible, with the researcher aiming to be outside the matter of enquiry, and thereby to ensure that the results are repeatable, regardless of the identity (or values) of the experimenter.

The epistemology of positivism is stark: it takes the view that only observable phenomena, independent of the researcher, provide a credible view of the world.

3.2.2 Realism

Saunders et al. [119] describe realism as a philosophy which relies on there being an objective reality, independent of the mind researching it. Conventionally divided into direct and critical realism, direct realism takes the view that our experiences are an accurate portrayal of an objective world and is broadly indistinguishable from positivism, while critical realism believes that sensations are impressions of an objective world requiring an appreciation of the context before conclusions can be drawn.

Unlike positivism, critical realism does not dogmatically require the use of the scientific method in developing useful research results but accepts that results can be influenced by the context in which they are derived.

In epistemological terms, realism accepts that observable phenomena can provide credible data and knowledge, but that context also contributes to a richer meaning of results.

In Technological Innovation Systems research, it appears that positivism/realism are the dominant paradigms, as researchers seek to systematically understand transitions and capture apparently objective data on the delivery of "functions". For example, Hekkert emphasised that "the analysis of technological change should focus on **systematically mapping** the activities that take place in innovation systems" [95], author's emphasis.

3.2.3 Interpretivism

Saunders et al. [119] explain that Interpretivism understands that "reality" is, at least in part, socially constructed, rather than objectively real. Within this understanding, Interpretivism recognises and accepts that the researcher and research subjects are themselves "social actors", who provide context and influence the perceived meaning in research outcomes.

Interpretivism therefore accepts (or even welcomes) that aspects of the "reality" being researched are socially constructed and are influenced by the values of both the researcher and the research subjects, rather than being objectively real. Under

Interpretivism, research into must take into account the relationships between the social actors participating in the space and the underlying features which these actors describe and can affect.

Interpretivist research often adopts more qualitative and experiential approaches than positivist and realist research philosophies, and it incorporates the values of the researcher, generating results that are subjective and interpreted.

Epistemologically, Interpretivism develops meanings that include the social phenomena which contribute to them.

MLP, which relies heavily on case studies, operates primarily within the interpretivist paradigm. As Yin [120] said, case studies stereotypically lead to unconfirmable conclusions, suggesting that they are within an interpretivist paradigm as one would expect positivist/realist data to be repeatable and confirmable. The selection of facts to include in a case study is certainly reliant on the researchers' views of what is important, and therefore by definition is subject to bias. Norris recognised this potential, pointing out that "consideration of self as a researcher and self in relation to the topic of research is a precondition for coping with bias" [121]. Genus and Coles asked whether MLP research had been "conducted in a sufficiently systematic manner" [106], again suggesting that researcher effects, characteristic of an interpretivist paradigm were at work. Papachristos [122] explicitly noted that "studies of transition frameworks are not based on a positivistic ontology", adding that the aim of research was to understand rather than predict. Geels, a leading MLP researcher, defended the interpretivist ontology, noting that is "interested in 'meaning'" [123].

It is clear that the field of transitions research has applied a range of philosophical paradigms – none is right or wrong, but awareness of the choices is, as Chapter 2 found, helpful in understanding different research traditions.

3.2.4 Pragmatism

As its name suggests, a pragmatic research philosophy is not driven by a single ontological or epistemological stance but adopts appropriate stances to fit the research questions being addressed.

The pragmatic approach draws as appropriate from the positivist and realist understanding of an objective reality and also from the interpretivist view that reality is, at least in part, socially constructed.

Equally, the pragmatic approach does not limit itself to the positivist/realist epistemology, in which only observable phenomena can provide credible data, or to the interpretivist approach, where meanings are subjective but which can provide richer, more interpreted understandings.

In conclusion to this section, the explanatory architecture set out by Saunders et al. [119], as summarised below, can be usefully adopted and adapted.

	Positivism / direct realism	**Critical realism**	**Interpretivism**	**Pragmatism**
Ontology	External reality is capable of being objectively characterised	External reality is objective, but under-standing of it is context sensitive	Reality is largely socially constructed, and may look different to different observers	Multiple viewpoints are valid, and each may provide valuable understanding of underlying reality
Epistem-ology	Only observable phenomena can provide credible data. Law-like general-isations are available and valuable	Observable phenomena illuminate reality, but context may affect interpretation	Only subjective interpretations of reality, influenced by social actors' and their values are available	Both observable phenomena and subjective interpretations are useful and meaningful
Role of values	None. Research is undertaken "value-free".	Researcher's values influence structure of	Research is value-driven, with the researcher and	Values play a part in interpretation; research aims

	Results are therefore independent of researcher values	enquiry and interpretation	research inseparable. Results unlikely to be repeatable	to recognise subjective and objective aspects
Data collection techniques most often used	Highly structured, numerical, measurement based	Can be qualitative or quantitative depending on subject matter	Qualitative, in-depth and small samples typical	Mixed or multiple methods, depending on research questions

Table 3-1: Based on Saunders et al. [119]*; author's additions and modification*

The research questions set out in Section 2.10 include those which clearly lend themselves to a positivist approach, and others which will require a more interpretivist perspective. From an overall stance, a pragmatist approach is clearly indicated.

3.3 Inductive and deductive approaches and adoption of philosophical framework

As Saunders et al. [119], p. 127 say, the difference between inductive and deductive approaches depends on whether the research starts from theory and seeks supporting data (deductive), or starts with the data and builds a theory to explain that data (inductive).

The core research question of whether the seven functions form a necessary and sufficient framework is split into two halves, each requiring a distinct theory-building/theory-testing approach.

Testing whether the existing seven functions are "necessary" requires a deductive approach, in which data is gathered to test this theory. In contrast, answering the question of whether the seven functions are sufficient requires an inductive approach in which the interview data and findings from the literature review are analysed to identify whether any additional functions appear to be necessary, and if so, what they are.

The research questions and consideration of philosophical frameworks strongly indicate that no single framework can guide all of this research.

Accordingly, it is proposed that a pragmatic philosophy involving both deductive and inductive reasoning approaches is taken, with the specific research questions guiding the philosophical framework on a case by case basis.

This will allow the research to include both subjective interpretations formed by actors in the sector (such as those qualitatively describing factors affecting the offshore wind niche break-out), and those which clearly relate to an objective reality (such as those concerned with cost evolution).

Moving further into the "onion", the natural choice of research strategy is "grounded theory", described by Saunders et al. [119], p 148-149 as "'theory building' through a combination of induction and deduction".

3.4 Moving from philosophical framework to methodology

The review of philosophical frameworks, approaches and research strategies has identified that a pragmatic philosophical framework is most appropriate to the research questions under investigation, applying both inductive and deductive approaches in a grounded theory strategy.

This strategy, and the research questions, will require mixed research methods, including semi-structured interviews and their analysis, and also quantitative analysis of interviewee responses. Table 3.1 below sets out each of the research questions, the choice of inductive or deductive approaches and design of research methods.

Research question	Preferred approach	Research methods	Expected outcomes
Is there a consensus characterisation of the seven functions model?	Deductive approach, grounded theory	Literature review and list reduction	Literature-supported list of functions to use as basis for interviews
Are the seven functions necessary and sufficient to	Interviewees' opinions on functions' roles are necessarily subjective. Deductive approach	Semi-structured interviews	Qualitative commentary on perceived importance of the functions

describe the technological change under consideration?	seeking data in support of "seven functions" model.		
What is the perceived importance of each function in delivering the transition?	Interviewees' opinions on functions' importance are necessarily subjective. Deductive approach seeking data in support of "seven functions" model	Interviewee scoring of perceived importance	Quantitative assessment of perceived importance of the functions
If these functions are not sufficient, what other function(s) are required?	Inductive approach to assess whether interviews suggest requirement for additional function(s)	Semi-structured interviews	Identification of new function(s) if required, based on analysis of interviews
How should any new function(s) be characterised?	Inductive approach to build theory of any new functions from interview data	Analysis of interviews, literature review, trial against example technologies	Proposals for definition and characterisation of any new functions for which a need has been identified
What lessons are relevant to the emergent wave and tidal stream sectors from the offshore wind experience?	Inductive approach to develop lessons from interview findings	Application of interview findings to perceived differences in offshore wind and wave and tidal	Commentary on lessons for wave and tidal stream from offshore wind
Is there scope to reconcile or integrate TIS and MLP approaches?	Inductive approach to identify scope for reconciliation / integration	Interpretation of interview responses, literature review, theory building	Commentary on potential for reconciliation or integration of TIS and MLP approach

Table 3-2: Research questions and philosophies (author's work)

This section describes the features of these methods and compares them with other techniques available, justifying the choices set out.

3.4.1 Quantitative methodologies

The quantitative research questions focus on gathering interviewees' scores on the perceived importance of each of the seven Hekkert functions, to provide an assessment of their perceived relative importance.

In addition, levelised costs of energy for offshore wind farms and a counterfactual CCGT power station were derived, based on a novel use of published accounting data. This analysis and methodology is described in depth in Aldersey-Williams et al. [63].

3.4.2 Qualitative methodologies

The qualitative research questions could legitimately be addressed through a number of methodologies. Applying Saunders et al.'s [119](p140) categorisation of research as exploratory, descriptive and explanatory, the research aim is clearly the last of these.

Available data gathering approaches lie on a spectrum of decreasing formality from questionnaire, fully structured interviews, semi-structured interviews and free form discussions. In addition to these one-to-one approaches, data gathering and generation can be undertaken in a panel discussion. Table 3-3 sets out features of each of these approaches.

Approach	Sample size	Quality of sample (relevance to and knowledge of research topic)	Specificity of response (how closely answers address questions)	Potential for statistical analysis	Potential for quali-tative analysis	Potential for emergence of new themes
Question-naire (questionnaire sent, responses requested)	Can be large, but response rate unpredict-able	Good for generalised research, poor for targeted research	Good – specific (numerical) responses to questions	Good – numerical responses ideal for statistical analysis	Poor – little scope for interpret-ation	Poor – defined structure and no opportunity for discussion
Survey / structured interview (question-naire completed with participant present)	Small, data gathering time consum-ing but response rate high	Good – small sample can be focussed on relevant range of participants	Good – respondents asked for specific (numeric) answers to specific questions	Good – numerical data gathered allows statistical analysis	Good – context behind numerical answers can be gathered allowing some qualitative analysis	Some – scope to identify new areas for enquiry, but unlikely to be "left field"
Semi-structured interview	Small, but more time consuming than structured. High response rate	Good – small sample can be focussed on relevant range of participants	Good – respondents asked for specific (numeric) answers to specific questions with extended context	Good – numerical data gathered allows statistical analysis	Good – context behind numerical answers can be gathered allowing some qualitative analysis	Good – semi-structured format introduces potential to identify new areas for enquiry; scope for freer discussion may introduce "left field" ideas
Unstruct-ured interview	Small, even more time consum-ing than structured. High response rate	Good – small sample can be focussed on relevant range of participants	Poor – unstructured interview may omit enquiry into overlooked areas, allow respondent to focus on limited (potentially parochial) scope	Poor – no numerical responses offers no scope for statistical review	Good – entirely qualitative responses offer scope for qualitative analysis (in those areas discussed)	Good – free flowing discussion may open up new areas for enquiry
Panel discussion Multiple partici-pants in	Small – for manage-ability	Excellent – invitees can be restricted to those with best knowledge	Good – panel can be directed to discuss specific areas of	Good – numerical data gathered, and ranges and	Some – although multi-party transcription can be	Some – discussion mostly directed in the interests of time

workshop setting		and sampling all participant segments (eg actors, academics, policy-makers etc)	enquiries and seek consensus and/or identify divergence in views	differences can be captured	complex and time consum-ing	manage-ment

Table 3-3: Features of data gathering approaches (author's analysis)

This analysis is consistent with Saunders et al's [119] analysis that semi-structured interviews are well suited to explanatory research.

It is concluded that semi-structured interviews offer the optimal mix of richness of data, flexibility of enquiry and use of available time resources.

These interviews were examined through qualitative content analysis, described in more detail in Section 3.5.6. Hsieh and Shannon describe qualitative content analysis "as a research method for the subjective interpretation of the content of text data through the systemic classification process of coding and identifying themes or patterns" [124]. This was clearly an appropriate approach to extracting qualitative comments on the functions from the interviews. The definition of categories of analysis is important: as Elo and Kyngäs [125] point out: "successful content analysis requires that the researcher can analyse and simplify the data and form categories that reflect the subject of study in a reliable manner." In this case, as explained in Section 3.5.6, the categories were initially defined by reference to the Hekkert functions, as justified in Chapter 4.

3.5 Interview process

3.5.1 Interviewee selection

At the outset of the study, a "wishlist" of potential interviewees was compiled from the researcher's professional network. Entries on this list were categorised into each of the categories defined for the study (wind and marine technology and project developers, supply chain, support organisations, policy makers and other stakeholders). As other meetings serendipitously took place at conferences and other industry events, other potential interviewees were approached about participating in the research.

I found that potential interviewees were, almost without exception, interested in the study and keen to participate. Accordingly, I arranged interviews with a representative sample of participants, both by exploiting existing network contacts and, in a very limited number of cases, by writing to other potential interviewees to ask for their participation. For example, my local Member of Parliament was not in my professional network, but I was able to contact his staff, and found that he was keen to participate. In some cases, existing contacts made recommendations of other interviewees, and these were added to the list in an example of snowball sampling [93].

In total, the wishlist ultimately reached around 60 potential interviewees. After completing around 30 interviews, it was apparent that consistent messages were emerging from the process and that "saturation" [126,127] had been achieved. At this stage, the interviewing process was concluded.

3.5.2 Interviewees

A total of 33 interviews were undertaken with senior participants in offshore wind, tidal stream and wave energy and their supply chain, together with appropriate policy makers and stakeholders. The interviews were undertaken in person in most cases (n=30) with a limited number undertaken by telephone (n=3). Only one interview was not used in the final research, as approval was not obtained for its use (see Section 3.5.8)

The interviewees were categorised into groups, to enable differential analysis of the perceived importance of functions between groups.

These groups were:

- MPD – marine project developer (n=3)
- MTD – marine technology developer/manufacturer (n=3)
- PM – policy maker (n=4)
- SC – supply chain (n=4)
- SH – stakeholder (n=7)
- SO – support organisation (n=4)
- WPD – wind project developer (n=4)
- WTG – wind turbine generator developer/manufacturer (n=3)

The participating organisations and their categories are shown in Table 3-4.

Organisations	Category
Atlantis	MPD
DP Energy	MPD
OpenHydro	MPD
Current2Current	MTD
EC-OG	MTD
Pelamis	MTD
BEIS	PM
Committee on Climate Change	PM
Member of Parliament	PM
Scottish Government	PM
Global Energy Group	SC
Gneiss Energy	SC
Scotia Supply Chain	SC
Subsea 7	SC
Crown Estate Scotland	SH
ORE Catapult (4)	SH
Robert Gordon University	SH
Scottish Enterprise	SH
Aberdeen Renewable Energy Group	SO
Carbon Trust	SO
Oil & Gas Institute, Robert Gordon University	SO
RenewableUK	SO
Kincardine Offshore Wind	WPD
Ørsted	WPD
SeaEnergy	WPD
Vattenfall	WPD
2-B Energy	WTG
MHI Vestas	WTG
Siemens Gamesa	WTG

Table 3-4: Participant organisations (author's analysis)

As participants were anonymous, it is not permissible to identify them individually. However, it is allowable to note that participants were generally at a high level within their organisations, with typical titles including Chief Executive, Member of Parliament, Director (both active and former), Senior Manager, Chairman (retired) and similar.

3.5.3 Interview structure

The interview structure was designed to address the research questions as set out in Section 2.10. The interviews were organised primarily according to the Hekkert functions, as this formed the principal thrust of the research. The interview structure therefore required an introduction, to brief interviewees about the aims of the research and the theoretical structure being investigated, before working through interviewees' views on each function in turn.

Finally, as the interviews were semi-structured, there was an opportunity for a more general discussion before gathering the interviewees' scores on their perception of the importance of each function.

The structure adopted for the semi-structured interviews is set out in Appendix 1.

3.5.4 Interview piloting

This structure was piloted with two respondents (one wind project developer, one stakeholder) and found to be useful and effective in eliciting useful information. It was found that the proposed 10-point measurement scale for scoring the interviewees' perception of the importance of each function was overly complicated, and this was reduced to a five point scale for future interviews as discussed below.

3.5.5 Interview data gathering

The interviews gathered both qualitative and quantitative information.
Interviewees were asked to discuss their views on the emergence of offshore renewable energy in the UK, and prompted with general descriptions of the seven Hekkert functions, to provide some structure to the discussions.

Quantitative scoring of the perceived importance of each of the seven functions was undertaken by asking interviewees to rate their perception of the importance of each of the seven functions on a Likert five-point scale [128]. Likert described a "symmetrical" five point scale, centred on a neutral mid point, while this research adapted that scale so that it describess levels of importance from zero to critical.

This scale was adopted after initial trials on a ten point scale indicated that interviewees were not able to resolve their views in this detail. This is consistent with findings reported by Birkett [129] who noted that "studies either found no relation between reliability and the number of response categories or demonstrated an inverted U-shape pattern with maximum reliability occurring with between five and seven response categories”. Accordingly, a five point modified Likert scale was adopted in which the scoring rubric was defined.

Score	Perception of function importance
1	Completion of the function has no effect on the emergence of the technology
2	Completion of the function has minimal effect on the emergence of the technology
3	Completion of the function has some effect on the emergence of the technology
4	Completion of the function has significant effect on the emergence of the technology
5	Completion of the function is essential to the emergence of the technology

Table 3-5: Scoring rubric (author's work)

3.5.6 Interview analysis

The tool used for qualitative content analysis was Nvivo (version 11). As interviews were undertaken, they were transcribed and uploaded to Nvivo. Once the first few interviews had been uploaded, an initial read-through was undertaken which allowed definition of classification “nodes”. These were broadly aligned with the seven Hekkert functions whose necessity was being tested, but the read-through also identified that another node was required to capture additional, substantive comments.

As the interviews were analysed, those interviewee comments fitting into the classifications for each of the seven functions were appropriately categorised. As these comments were categorised, sub-nodes were created to capture themes within each comment, in what was an iterative process.

In parallel, substantive comments from interviewees which did not fit cleanly into the existing nodes (and sub-nodes) were coded into the new node. This node was initially described as “techno-economic viability” but came to include comments on the actual and potential economic, social and environmental value of the emergent technology, often in the context of competing emergent and incumbent technologies, as further interviews were undertaken.

The nodes were:

- Entrepreneurial activities (F1)
- Knowledge development (F2)
- Diffusion and networking (F3)
- Guidance of the search (F4)
- Market formation (F5)
- Creation of incentives (F5)
- Resource mobilisation (F6)
- Legitimation (F7)
- Techno-economic viability – this node emerged during the analysis of the interviews and comprised interview comments relating to the comparative technical and economic potential of the focal TIS. It was influential in shaping the definition of the proposed new function which was identified and is described in chapters 6, 7 and 8.

3.5.7 Experiences of interviews

The participation of almost all interviewees was engaged, frank and enthusiastic. In many cases, interviewees were close professional acquaintances of the researcher and it is likely that this contributed to both their agreement to participate in the study and to the degree of engagement they showed. The opportunity to talked unguardedly about subjects of interest to interviewer and interviewee and share time thinking about the evolution of these sectors outside the scope of normal day-to-day business seemed to be an unusual and welcome opportunity, and was gratefully taken by participants. The exception was an interviewee not previously personally known to the researcher, who may have felt that it was part of their normal day to day responsibility to participate in research of this kind, but who appeared to be more reserved and keener to convey a "corporate" message than to share personal insights. This interview nonetheless contained useful insights and contributed to the findings.

While the interviewees were clearly keen to help with my research, I do not consider it to be a major risk that their answers were skewed or distorted to help me. The interviewees were professional and senior personnel, whom I had asked to be candid, and they understand the nature of academic research and the value of honest answers. Additionally, as this was grounded theory work, at least in the early interviews it wasn't clear necessarily to the participants what I was specifically looking for.

It is worth noting the quality of findings was in large part due to the senior nature of the interviewees: researchers seeking to build on these findings with similar studies may find it harder to engage an equivalent network of research interviewees.

3.5.8 Post-interview process

After each interview was completed, it was transcribed. This process employed a web-based service called Trint.com to produce the initial transcript, which was then edited for corrections manually and any inadvertent identifying comments anonymised. Each completed transcript was sent to the relevant interviewee for approval and editing. In most cases, the interviewee simply approved the transcript, although a small number accepted my invitation to edit and improve their answers (or to detune any particularly charged comments). All of the potential interviewees who were asked to participate agreed to do so, and only one of the 33 interviewees failed to reply to multiple requests for approval of their transcript, resulting in 32 completed interviews available for analysis. No reason is known for this one failure of response.

3.5.9 Approvals and ethics

Following the interview analysis, as the thesis was being written up, each interviewee was asked for approval of the specific quotes from their interview that were to be included. Again, in most cases, interviewees agreed and approved the quotes, although a limited number chose to modify their quotes to better (or more neutrally) express their views.

The ethical considerations in this research centred on anonymity of interviewees. This was ensured by coding interviewees with a code number comprising their category (wind and marine technology and project developers, supply chain, support organisations, policy makers and other stakeholders) and their serial number in the wishlist. The list of interviewees was held in a password protected file. All interviewees were assured of anonymity and agreed to participate on this basis.

Written permission to use the interview materials was obtained from interviewees at two stages: they were first asked to confirm that the transcript was acceptable, and later asked to confirmation that the use of extracts and quotations from their transcript was acceptable. In every case, written confirmation was received at both stages.

3.6 Defining the socio-technical transition

As described in Sections 2.4, 2.5 and 2.6, definition of the Technological Innovation System under review is critical. The system considered by this study comprises marine renewable energy technologies, including offshore wind, tidal stream and wave energy, in the overall context of large-scale (grid connected) power generation system of the UK, from 2000 until the present day.

3.6.1 Focal technologies under consideration

The focal technologies under consideration in this research are offshore wind, tidal stream and wave energy. Although offshore wind appears quite different from tidal stream and wave energy from the perspective of 2020, at the outset of the period covered by this study, the technologies appeared to share many characteristics, making their grouping appropriate. The key shared characteristics were:

- **Stage of technological development:** in 2000, all of these technologies were at a very early stage of development. Prototypes had been, or were soon to be deployed in all cases (e.g. Blyth offshore wind farm [48], Salter's "Edinburgh Duck" [130], Kobold turbines in the Straits of Messina [131]), but the technologies were very much experimental
- **Technical challenges:** the three technology families clearly shared comparable challenges: design, manufacture, installation and operation of complex electro-mechanical devices in the hostile marine environment
- **Supply chain:** it was expected that these technologies would be likely to draw on a strongly overlapping supply chain. It appeared that the oil and gas supply chain would be critical, as it had developed many of the skills required to address the known challenges

- **Output intermittency:** all of these technologies provide intermittent generation, although tidal stream is highly predictable, while offshore wind and wave energy share comparable intermittency characteristics
- **Policy support:** finally, Government policy in relation to all of these technologies was highly comparable. They were initially offered support under the Non-Fossil Fuel Obligation orders and latterly became eligible for Renewable Obligation Certificates [132]. Once banding was introduced to the Renewables Obligation, support began to stratify in response to the perceived level of financial support required [79]

With the benefit of hindsight, it is clear that offshore wind has achieved far more than tidal stream and wave energy, and the question of how and why this has been achieved ties into the research questions.

3.6.2 TIS definition

The Multi-Level Perspective considers actors, technologies, institutions (including both formal and informal); the TIS approach focusses more on technologies and innovation processes. These aspects of the study are set out in Table 3-6, which explains how the energy system is defined in this research.

Category	Included in system	Comments
MLP - Actors	Power generators (e.g. Centrica, Eon, RWE, Drax, etc) Wind farm developers (e.g. DONG, SSE, etc) Regulators (OFGEM) Policy makers (UK Government, Scottish Government, EU) Universities Technology developers (wind, wave, tidal)	Some power generators became wind farm developers
MLP - Technologies	Conventional power generation (coal, gas, nuclear, hydro) Emerging renewable power generation (onshore wind, biomass, offshore wind, wave, tidal)	Innovation focus is on offshore wind, wave, tidal Onshore wind innovation will also be considered
MLP – Institutions	Legal framework, including NETA/BETTA, Renewables Obligation etc	Evolution of regulatory regime a critical landscape/regime factor

Technological systems – economic competence	Capability of actors to exploit new business opportunities	Not directly addressed in MLP model.
Technological systems – clustering	Economies of scale and learning opportunities arising from innovation	Does not map explicitly to MLP model, but will be considered within institutions
Technological systems – networks	Networks of technology developers, universities, funders, Government and NGOs	Maps closely to MLP actors. In TIS only includes actors positive towards innovation; MLP includes actors seeking to maintain regime lock-in
Technological systems – development blocks	Creation of markets, technologies	Maps closely to MLP technologies and institutions
Technological systems – institutional infrastructure	NETA/BETTA, Renewables Obligations, grant funding, EU directives, UK laws, investment appetites	Maps closely to MLP - institutions

Table 3-6: Elements of integrated system (author's work)

3.7 Contribution to the "functions" methodology

In the literature, as summarised in chapter 2, a number of authors (including, for example, Hekkert et al. [95], Johnson [133] and Jacobsson et al. [134]) have described lists of functions but say little about their origins. Similarly, Jacobbson and Karltorp [113] describe using a list of functions, but do not explain the source of this list, and Negro et al. [144] again simply provide a table entitled "Set of Functions of Innovation Systems" without any source or justification. Many researchers appear to accept pre-existing sets of functions, and move directly to assessing their performance.

Bergek et al. [92] describe developing a set of functions "based on several literature reviews and a number of empirical studies", but provide very limited further detail. Hekkert et al. [116] came closest to the approach in this research, seeking to apply an empirical validation to a set of functions, but they did this only by reference to published information, "retrieving as many events as possible …using…newspapers, magazines and reports" to identify events supporting the existing functions inventory. They did not seek to involve stakeholders in the transitions in question.

Only Hekkert and Negro [116] attempted an empirical validation of "whether the functions of innovation systems framework is a valid framework to analyse processes of technological change". Their work, however, relied entirely on published data, including "newspapers, magazines and reports", accessed via LexusNexus®. Researchers appear to consider functions inventories to be robust, and move directly to seeking evidence to support them.

This research adopts a new empirical and stakeholder-grounded approach to the definition of functions and to their relative importance. This is, it is believed, a new approach to methodology in the context of functions in TIS.

3.7.1 Stakeholder salience versus stakeholder-grounding

Stakeholder salience is a theory which seeks to understand how managers assign priority to competing stakeholder claims [135].

According to Mitchell, managers make decisions in the light of the relative importance or "salience" of stakeholders in their businesses. Stakeholders are seen to have attributes of "power", "legitimacy" and "urgency", with managers allocating priority to decisions based on their perception of these attributes. Agle et al. [136] confirmed this idea, finding a significant correlation between these attributes and stakeholder salience.

Stakeholder salience assessment is a process by which the salience of stakeholders to a project or decision or set of decisions is quantified and analysed, [137] in order to ensure that the most salient stakeholders are given the most weight in relevant decisions. Salience assessments can be delivered numerically or visually, and enable decisions to be taken with an informed view of the relative importance of stakeholder interests. Stakeholder salience assessment can define stakeholders as individuals or actors, or as wider interests. For example, Kinnunen et al. [137] defined stakeholders as interests in product development (such as "Design for Testing" and "Design for Packaging"), and found that this produced useful conclusions.

While the core idea of salience assessment – that of finding and quantifying the relative importance of factors in decision making – is clearly similar to the consideration of the perceived importance of the seven "Hekkert" functions in this research, there are differences between the approaches. Stakeholder salience assessment seeks to identify the most important stakeholder (or factor). In contrast, the stakeholder-grounded assessment used in this research does not seek to find only the most important factor, it seeks to identify which of all of the factors are salient. The quantitative techniques developed by stakeholder salience assessment, such as quantification of power relationships by direct comparison, are not relevant in this less formal approach.

Accordingly, whilst stakeholder salience assessment has been considered, it is concluded that it aims at a quite different result to the stakeholder-grounded assessment of perceived importance undertaken in this research.

4 Analysis of proposed functions and selection of core functions

This chapter starts to apply the methodology set out in Chapter 3 by considering the various inventories of functions proposed in the literature and described in Section 2.3.3. It attempts to develop a comprehensive and justifiable list of functions by reviewing and grouping functions within these inventories.

It is divided into three sections. Section 4.1 identifies various inventories of functions offered in the literature, and applies a list reduction approach to develop a single inventory which aims to be comprehensive and justifiable. Section 4.2 summarises the definitions of the functions proposed in the comprehensive, list, and Section 4.3 explains the new functions list, and notes where particular effort was required to reconcile functions inventories from the literature.

4.1 Classification and list reduction

The concept of functions in innovation systems was first proposed around the turn of the millennium by Johnson [133], and has been developed, adjusted and refined by many authors since then.

All of these authors have taken as axiomatic that the innovation systems being considered were operating in well-configured capitalist systems. As American Founding Father Alexander Hamilton recognised, capitalist societies must "establish rule of law through enforceable contracts, respect private property, create a trustworthy bureaucracy to arbitrate legal disputes and offer patents and other protections to promote invention" (p. 345) [138].

With these preconditions assumed to be in place, the notable authors considering functions within Technological Innovation Systems have been Bergek et al. [139], Bergek and Jacobsson (cited in Bergek Bergek (2008) [92]), Carlsson and Stankiewicz [87], Galli and Teubal [140] and Hekkert et al. [95]. Each of these authors has developed a slightly different set of functions, whilst sharing the view that the "functions" are key processes which "directly influence the development, diffusion and use of a new technology, and thus the performance of the innovation system" [139]. These authors generally developed their lists of functions by conceptualising the problem and with reference to other literature: little evidence was found of authors validating these functions lists with relevant stakeholders.

In an attempt to impose some order, Bergek et al. [139] developed a comparative table of the various definitions of functions which they mapped into their seven function definition. This section critically assesses that simplification. It has taken the approach of listing all of the functions defined by each of the authors in the Bergek et al. paper, of which there are 70, and identifying groupings into which these functions appear to fall. Eight groupings have been identified.

The complete list of functions proposed by authors reviewed by Bergek et al. [139] has been extracted into Table 4-1. Each listed function has been considered and fitted into one of eight new groupings.

Seven of the emergent groupings are closely related to Bergek et al.'s seven functions, and are identical to those proposed by Hekkert et al. [95]. These are: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resource mobilisation, and legitimation.

An eighth grouping is "creation of incentives", which appears as a function in three authors' work and where it is defined as "provide incentives for entry" [133], "creating incentives" [87], and "creating/changing institutions that provide incentives or obstacles to innovation" [141].

This eighth grouping is supported by the interviews undertaken in this research.

Function as defined by researcher	**Author ref.**	**Natural grouping**
Knowledge development	A	Knowledge development
Knowledge diffusion	A	Diffusion and networking
Entrepreneurial experimentation	A	Entrepreneurial activities
Influence on the direction of search	A	Guidance of the search
Market formation	A	Market formation
Development of positive external economies	A	Legitimation
Legitimation	A	Legitimation
Resource mobilization	A	Supply resources

Create knowledge	B	Knowledge development
Facilitate information and knowledge exchange	B	Diffusion and networking
Create knowledge	B	Knowledge development
Identify problems	B	Knowledge development
Guide the direction of search	B	Guidance of the search
Provide incentives for entry	B	Creation of incentives
Recognise the potential for growth	B	Entrepreneurial activities
Stimulate market formation	B	Entrepreneurial activities
Facilitate information and knowledge exchange	B	Diffusion and networking
Counteract resistance to change	B	Legitimation
Supply resources	B	Supply resources
Create human capital	C	Knowledge development
Direct technology, market and partner search	C	Guidance of the search
Create technological opportunities	C	Knowledge development
Diffuse technological opportunities	C	Diffusion and networking
Create market	C	Market formation
Diffuse market knowledge.	C	Diffusion and networking
Facilitate regulation (may enlarge market and enhance market access)	C	Guidance of the search
Enhance networking	C	Diffusion and networking
Legitimize technology and firms	C	Legitimation
Facilitate financing	C	Supply resources
Create a labour market	C	Supply resources
Incubate to provide facilities, etc.	C	Entrepreneurial activities
Create products (materials, parts, compl. products)	C	Knowledge development
Diffuse products (materials, parts, compl. products)	C	Diffusion and networking
Create new knowledge	D	Knowledge development
Create knowledge	D	Knowledge development
Guide the direction of the search process	D	Guidance of the search
Facilitate the formation of markets	D	Market formation
Facilitate the creation of positive external economies	D	Legitimation
Supply resources	D	Supply resources
Creating a knowledge base	E	Knowledge development
Promoting entrepreneurial experiments	E	Entrepreneurial activities
Creating incentives	E	Creation of incentives
Creating markets or appropriate market conditions	E	Market formation
Promoting positive externalities, or ‘free utilities’	E	Legitimation
Creating resources (financial and human capital)	E	Supply resources

Provision of R&D, competence building	F	Knowledge development
Creating and changing organizations needed (e.g. enhancing entrepreneurship)	F	Entrepreneurial activities
Articulation of quality requirements (demand side)	F	Market formation
Creating/changing institutions that provide incentives or obstacles to innovation	F	Creation of incentives
Articulation of demand	F	Entrepreneurial activities
Prioritizing of public and private sources (the process of selection)	F	Guidance of the search
Formation of new product markets	F	Market formation
Articulation of quality requirements (demand side)	F	Market formation
Networking	F	Diffusion and networking
Creating/changing institutions that provide incentives or obstacles to innovation	F	Guidance of the search
Financing of innovation processes, etc	F	Supply resources
Provision of consultancy services	F	Supply resources
Incubation activities	F	Entrepreneurial activities
R&D diffusion of information, knowledge and technology	G	Diffusion and networking
Diffusion of information, knowledge and technology.	G	Diffusion and networking
Professional coordination	G	Guidance of the search
Design and implementation of institutions.	G	Guidance of the search
Diffusion of scientific culture	G	Diffusion and networking
Supply of scientific and technical services	G	Supply resources
Creation of technological knowledge	H	Knowledge development
Regulation and formation of markets	H	Market formation
Articulation of demand	H	Market formation
Exchange of information through networks	H	Diffusion and networking
Development of advocacy coalitions for processes of change	H	Legitimation
Supply of resources for innovation	H	Supply resources

Table 4-1: Full list of functions (author's analysis)

Key to authors:

Key	Author and citation
A	Bergek (2008) [92]
B	Johnson, (1998, 2001) [133], Bergek [142]
C	Rickne [143]
D	Bergek and Jacobsson (various), cited in Bergek (2008) [92]

E	Carlsson and Stankiewicz (2005) [87],
F	Edquist (2006) [141]
G	Galli and Teubal (1997) [140]
H	Hekkert et al. (2007) [95]

Table 4-2: Key to authors in function analysis (author's analysis)

Hekkert et al's and Bergek et al.'s functional definitions closely overlap, so it worth exploring their differences. This close overlap comes as little surprise, as Marko Hekkert was a contributing author on Bergek et al.'s [92] 2008 paper which originally defined the functions. The key differences lie in Hekkert et al.'s [95] definition of knowledge development and knowledge diffusion as discrete functions, and their exclusion of Bergek et al.'s [92]. function of "development of positive externalities".

The separation of Bergek et al.'s combined knowledge development/diffusion function by Hekkert et al. allows for a clear differentiation of the development of new knowledge through R&D activities, which can be restricted to a single participant in an emerging TIS, and knowledge diffusion which allows for such new knowledge to be shared between participants in the TIS.

The other key difference is the exclusion by Hekkert et al. of Bergek et al.'s final function – "development of positive externalities". Even Bergek et al. [92] seem to be half-hearted in their commitment to this function, as - while they accept that renowned researcher and writer Michael Porter describes positive externalities as "central to the formation of innovation systems" - they note that the processes by which these positive externalities emerge are "not independent of other functions" but are indicative of healthy dynamics of an innovation system on a functional level.

Practitioners seeking to apply the functions approach in TIS, such as Negro et al. [144] and Hannon et al. [97] have commonly adopted the Hekkert et al. [95] functions definitions, which appear to have become authoritative.

This analysis confirms that all of the various functions identified by the authors reviewed can sensibly be mapped into Hekkert et al.'s seven functions, subject only to the decision to subsume "Creation of Incentives" within Hekkert et al.'s "F4 – Guidance of the Search", and these functions definitions may reasonably considered as an authoritative list.

4.2 Functional definitions

The definition of each of the seven natural groupings applied in this work is set out below, followed by a list of the unique functions identified in Bergek et al.'s [139] review which map to that natural grouping.

It is immediately clear that these the groupings overlap, both in terms of the activities which contribute to the success of each function, and temporally, where multiple functions may be active in a transition at any time. These functions overlap both in scope and temporally. The temporal relationships of functions are explored in Section 5.9.2, in the light of the research interviews.

4.2.1 F1 – Entrepreneurial activities

Entrepreneurial activities comprise the activities which enable the early stages of a transition to take effect. They may be undertaken by new participants in the sector or involve diversification activities undertaken by existing participants. They can include R&D activities (which may overlap into F2- Knowledge development) and/or market validation and awareness building (which may run into F5 – Market formation or F7 – Legitimation).

Entrepreneurial experimentation
Recognise the potential for growth
Stimulate market formation
Incubate to provide facilities, etc.
Promoting entrepreneurial experiments
Creating and changing organizations needed (e.g. enhancing entrepreneurship)
Articulation of demand
Incubation activities

Table 4-3: Functions within F1 - Entrepreneurial activities (author's analysis)

4.2.2 F2 - Knowledge development

Knowledge development comprises research and development activities, which improve the technology itself, or the value of applying the technology, through innovations in ancillary technologies (eg installation of offshore wind turbines), funding strategies, risk management strategies or other improvements.

It can be undertaken by research bodies, such as universities or support organisations (such as the Offshore Renewable Energy Catapult), by industry participants directly or by joint industry projects funded by industry participants and coordinated by support organisations (such as the Carbon Trust's Offshore Wind Accelerator programme).

Knowledge development
Identify problems
Create human capital
Create technological opportunities
Create products (materials, parts, compl. products)
Create new knowledge
Create knowledge
Creating a knowledge base
Provision of R&D, competence building
Creation of technological knowledge

Table 4-4: Functions within F2 - Knowledge development (author's analysis)

4.2.3 F3 - Knowledge diffusion and networking

Knowledge diffusion and networking comprises the exchange of information among stakeholders to the transition. It can include both formal information sharing efforts, such as Government dialogue with trade associations to better define policy choices, and informal diffusion of knowledge, such as happens when employees move employer.

Knowledge diffusion
Facilitate information and knowledge exchange
Facilitate information and knowledge exchange
Diffuse technological opportunities
Diffuse market knowledge.
Enhance networking
Diffuse products (materials, parts, compl. products)
Networking
R&D diffusion of information, knowledge and technology
Diffusion of information, knowledge and technology.

Diffusion of scientific culture
Exchange of information through networks

Table 4-5: Functions within F3 - Knowledge diffusion and networking (author's analysis)

4.2.4 F4 – Guidance of the search, including creation of incentives

Guidance of the search is centred on policy design, at international, national, subnational, regional and local levels, and considers regulatory development aimed at enabling a transition (such as Strategic Environmental Assessments for offshore wind development areas and development of standards), and explicitly includes the creation of incentives as policy instruments (which could equally be considered F5 – Market formation).

Influence on the direction of search
Guide the direction of search
Direct technology, market and partner search
Facilitate regulation (may enlarge market and enhance market access)
Guide the direction of the search process
Prioritizing of public and private sources (the process of selection)
Creating/changing institutions that provide incentives or obstacles to innovation
Professional coordination
Design and implementation of institutions.
Provide incentives for entry
Creating incentives
Creating/changing institutions that provide incentives or obstacles to innovation

Table 4-6: Functions within F4 - Guidance of the search, including creation of incentives (author's analysis)

4.2.5 F5 – Market formation

Market formation comprises the activities of ensuring that there is a viable demand for the transition being considered. In the case of offshore wind, it is clear that the overall electricity market is broad and deep enough to accommodate any generating technology, at least up to a level of generation, as long as it is commercially viable. As penetration grows, consideration of grid stability, management of intermittency and other factors specifically bearing on offshore wind and marine renewables become part of the market formation function.

Market formation
Create market
Facilitate the formation of markets
Creating markets or appropriate market conditions
Articulation of quality requirements (demand side)
Formation of new product markets
Articulation of quality requirements (demand side)
Regulation and formation of markets
Articulation of demand

Table 4-7: Functions within F5 - Market formation (author's analysis)

4.2.6 F6 – Resource mobilisation

Resource mobilisation describes the function of allocation of people, resources, equipment and funding to enable the maturation of the TIS.

F6 – Resource mobilisation is closely related to F1 – Entrepreneurial activities, in that both are concerned with the allocation of necessary resources. The key difference is that F1 is concerned with those activities which typically take place at the early stage of the TIS niche breakout, in the form of invention and innovation, early fund raising, market creation and legitimation, while F6 - Resource mobilisation is much more "business as usual" and addresses the allocation of conventional resources to deliver the upscaling of a transitional technology.

Resource mobilization
Supply resources
Facilitate financing
Create a labour market
Creating resources (financial and human capital)
Financing of innovation processes, etc
Provision of consultancy services
Supply of scientific and technical services
Supply of resources for innovation

Table 4-8: Functions within F6 - Resource mobilisation (author's analysis)

4.2.7 F7 – Legitimation

The function of "Legitimation" is rooted in Bergek et al.'s definition of a function comprising "the development of positive external economies" [92]. However, even Bergek and her co-authors seem to be half-hearted in their commitment to this function. While they accept that renowned researcher and writer Michael Porter describes positive externalities as "central to the formation of innovation systems", they note that the processes by which these positive externalities emerge are "not independent of other functions but works through strengthening the other six functions" [92].

Hekkert et al.'s [95]wider definition of a function of legitimation, includes the creation of positive externalities with the broader factors of building societal support and counteracting resistance to change. This broader legitimation function is a common feature of many of the authors reviewed and is seen as an important aspect of a successful TIS. In MLP terms, the legitimation function can contribute to regime destabilisation, by building the case for new technologies or against incumbent technologies, and can influence the landscape, by again making the case for the transition.

Development of positive external economies
Legitimation
Counteract resistance to change
Legitimize technology and firms
Facilitate the creation of positive external economies
Promoting positive externalities, or 'free utilities'
Development of advocacy coalitions for processes of change

Table 4-9: Functions within F7 - Legitimation (author's analysis)

4.3 Selection of functions for analytical framework

The first and most important observation is that the functional definitions are closely consistent in almost all cases. This comes as little surprise, as Hekkert was a contributing author on Bergek et al.'s [92] 2008 paper which proposed definitions for TIS functions and many of the authors cited here have published together on these topics.

The key differences lie in Hekkert et al.'s [95] definition of knowledge development and knowledge diffusion as discrete functions, and their replacement of Bergek et al.'s [92] function of "development of positive externalities" with the wider "legitimation".

In addition, the creation of incentives might be considered an independent function, or to be contained within Guidance of the Search or Market Formation. In this analysis, the importance of Government (whether National or sub-national, and whether influenced by trans-national priorities or not) is recognised to be the critical factor in the creation of incentives. Accordingly, creation of incentives has been included with the function of "Guidance of the Search".

4.3.1 Knowledge development and diffusion

In practice, and as confirmed by the interviews undertaken for this work, it appears that some knowledge diffusion is an unavoidable side effect of knowledge development, at least in a commercial setting, because employees move between employers and take knowledge with them.

Bergek et al. [139] take this view, and define their knowledge development and diffusion function as capturing "the breadth and depth of the current knowledge base of the TIS, and how that changes over time, including how that knowledge is diffused and combined in the system".

However, where explicit knowledge diffusion activities are perceived to play an important role in the development of a TIS, there is a case to be made that the two functions are sufficiently distinct to be usefully separated. In the case of offshore wind, the activities of a number of supporting institutions have been specifically designed and funded to drive diffusion of knowledge and networked efforts in knowledge development. In the UK, these institutions include the Carbon Trust (working principally through the joint industry projects undertaken under the auspices of the Offshore Wind Accelerator), the Offshore Renewable Energy Catapult, the Offshore Wind Energy Council (OWIC) and Offshore Wind Energy Group (OWIG) and the Energy Technology Institute, while on a Europe-wide basis the European Wind Energy Technology Platform (TPWind) undertook a similar function.

Consequently, Hekkert's model for the "knowledge" functions in TIS, separating knowledge development from knowledge diffusion and networking has been adopted for this research.

4.3.2 Legitimation

The wider definition of legitimation, which includes the building of societal support and challenge to resistance to the innovation, is described by Bergek et al. [92] as "not independent, but works through strengthening the other six functions". However, Hekkert et al. [95] consider this as a full function, and broaden the definition to include the formation of "advocacy coalitions" which can contribute to the drive behind many of the other functions. They specifically point to the contribution made by such coalitions towards guidance of the search and allocation of resources, although it can be added that legitimation of a new technology can also contribute strongly to the formation of a market for that technology.

4.3.3 Seven core functions

This chapter has critically reviewed the long list of functions proposed by a number of leading researchers in the area of TIS and has resolved these into seven core functions. The seven resolved functions are now defined as "core" functions which closely match the widely-used set of seven functions defined by Hekkert et al. [95]

In the following chapters, this research investigates the question of whether these seven core "Hekkert" functions form a necessary and sufficient framework within which to consider technological transitions with specific reference to the emergence of offshore wind, tidal stream and wave energy in the UK since 2000.

5 Exploring the necessity of TIS functions

The key research question which has emerged in this work is whether the "seven functions" model provides a "necessary and sufficient" framework for describing the technological transition under consideration. Building on the functions list developed in Chapter 4, this chapter focuses on the first half of that question, by exploring the perceived validity of the seven "Hekkert functions.

The subsequent chapter addresses the second half of the question, by considering whether these seven functions form a sufficient framework to fully characterise the socio-technical transition.

5.1 Structure of this chapter

This chapter is the most complex in the thesis, as it considers each of the seven Hekkert functions in parallel, before bringing this analysis together to address the inter-relationships between these functions.

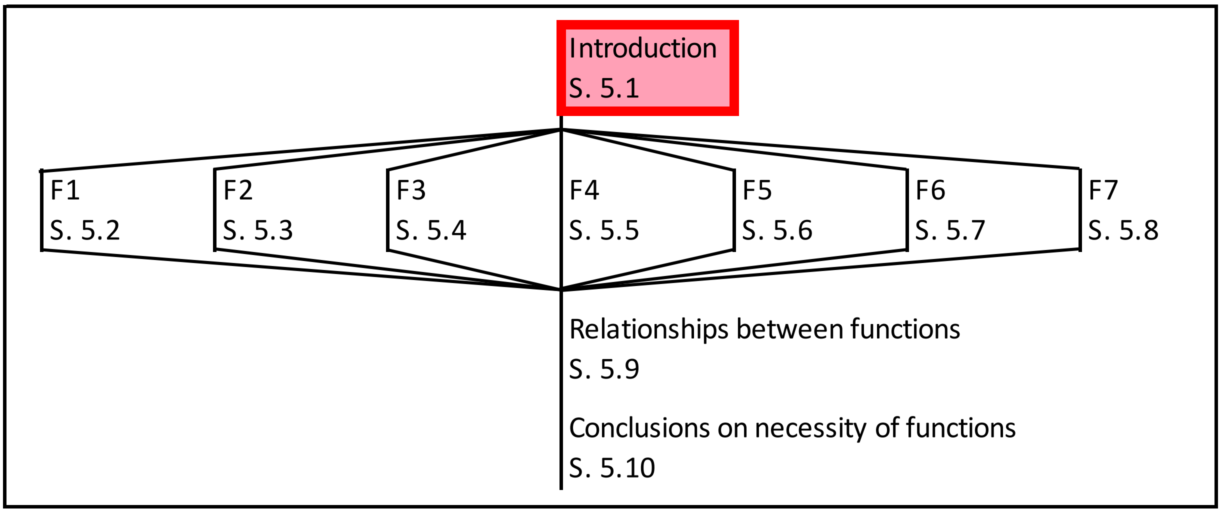

Figure 5-1: Section 5.1 roadmap

Each major section in this chapter is prefaced with a version of Figure 5-1 to provide a visual roadmap for navigation within the chapter.

The following Sections, 5.2 - 5.8, describe the research findings in relation to each function. Each of these sections is divided into 6 subsections:

- a general discussion of the findings in relation to each function, including comments on the key themes which emerged;
- a breakdown of key findings for each function along the TIS dimensions of actors, networks and institutions defined by Carlsson and Stankiewicz [87] and refined by Bergek [92];
- a review of metrics, indicators and drivers emerging from the interviews;
- an exploration of the perceived validity of function, including an assessment of the scores given by interviewees; and
- a conclusion in which the function is defined in light of the interview findings.

Section 5.9 draws these findings together by considering the operational and temporal relationships between functions and Section 5.10 concludes this part of the review of the interviews.

As reviewed in chapter 4, the wide range of functions in Technological Innovation Systems (TIS) can be simplified into those defined by Hekkert et al. [95]. This function set forms the basis of the analysis in this research, and the interviews with the sample set of interviewees have been analysed to extract insights into the perceived validity of each of these functions in the TIS under investigation, together with suggestions of metrics, "drivers" and "indicators" of each function.

5.1.1 Functional validity and testing

One of the research questions of this study asks whether the "seven functions" model provides a necessary and sufficient framework to explain technological emergence. This question is addressed by testing the validity of the seven "Hekkert" functions [95]. This was done by seeking the views of the interviewees on their perception of the importance of each function.

There might be some risk that the interviewees are suffering from "groupthink" [145] in relation to the existence of these functions and this was explored.

As interviewees were previously unaware of the TIS theoretical framework, or the definitions of functions before the interviews, it seems unlikely that this is the case, and it seems more likely that the functions describe "real-world" factors which genuinely bear on the emergence of the technology. However, this work specifically interrogates the interview in which the lowest score for each function was recorded, to see if that provides any insights as to whether any function is unnecessary.

In general, the high scores recorded for each function give considerable confidence that all seven "Hekkert" functions are necessary. It does not address the question of sufficiency, which is the subject of Chapter 6.

5.2 F1 - Entrepreneurial Activities

"You won't have the entrepreneurs unless there's a genuine opportunity for them to exploit" – SH43

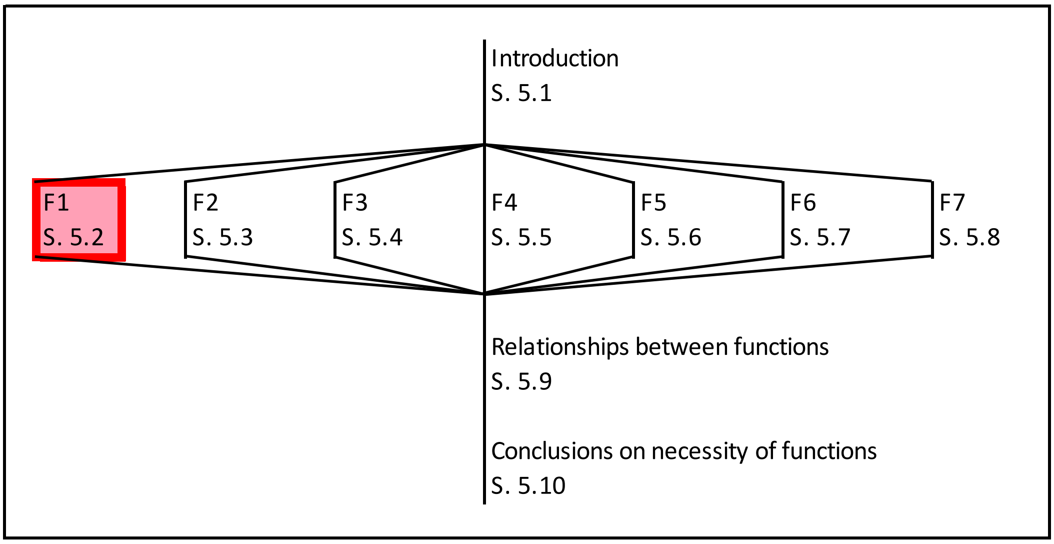

Figure 5-2: Section 5.2 roadmap

5.2.1 Key themes

Entrepreneurial activities were widely recognised to be a key factor in the emergence of the offshore wind TIS and in the evolution of the tidal stream and wave TISs.

Key themes that emerged during the interviews were:

- the different types of entrepreneurial activity that took place,
- the motivation of entrepreneurs,
- the need for an entrepreneurial culture,
- the difference in entrepreneurial activities between offshore wind and the marine (tidal stream and wave) sectors, and
- the impact of competitive pressures on entrepreneurial activities

5.2.1.1 Different types of entrepreneurial activity

Although the core turbine technology for offshore wind was readily developed from onshore wind, many interviewees also referred to the need for entrepreneurial activities in a wide range of supporting activities, including supply chain development, licensing and regulatory support and financing.

SH36 noted this in the regulatory area:

> *"I think that it took innovative individuals – it always does – those who are willing to forge new paths in consenting, leasing and regulations as well..." – SH36*

The requirement for entrepreneurial activities, and their taking place in large companies as well as in smaller organisations, was also clearly recognised:

> *"the entrepreneurship became partly linked to innovation but it was more hidden - it was in contractors and supply chain, and it was inside big companies." – SO34*

It was found that entrepreneurial activities could take place in a range of environments, from single individuals working alone, through small groups in research institutions and corporate environments, and in larger corporate settings. Interviewees' recollections of this were varied. Some felt that small groups or even individuals had been the driving force:

> *"There was a set of relatively young people who were given some flexibility - some in research institutions, some in commercial bodies" - SO34*

While others felt that the corporate setting was critical:

> *"I am not aware of any particular shining individuals. It's more a corporate story…the entrepreneurial activity was a state backed thing" - PM30*

It is likely that these different perspectives reflect the different kinds of entrepreneurship at different stages of development, as well as the particular perspective of each interviewee.

In particular, in the marine sector where individuals or very small companies were (and are) instrumental in developing new wave and tidal stream technologies, entrepreneurship is concentrated in small groups. In contrast, offshore wind project development is now a maturing business with large capital requirements, and entrepreneurship is more focussed on incremental improvement and innovation in deployment, operations and financing.

5.2.1.2 Motivation

The motivation for entrepreneurial activities was widely discussed, and different motivations were seen as relevant in different circumstances. These included curiosity, especially in the case of wave and tidal:

> *"I wouldn't even necessarily describe the early activities as entrepreneurial. These were enthusiastic engineers, and academics in some cases, who just wanted to demonstrate that it could be done." – WTG15*

> *"A lot of people get the buzz out of creating some new technology but they don't want anything to do with creating a business" – MTD64*

Other motives were simply commercial:

> *"You won't have the entrepreneurs unless there's a genuine opportunity for them to exploit" – SH43*

> *"If you want to be in the future of the big organisations, in whatever shape or form, you will have to be in the energy transition" - SO60*

Other motives were practical:

> *"the asset manager for Beatrice*[2] *was looking at not necessarily renewable energy but how do you get extra life out of an oil and gas platform?" – SC14*

The desire to establish a leadership position in a sector that was seen to be emergent was also a common motivator. SC14 found that their organisation had clearly defined its motivation to participate in the emergent offshore wind sector as a way of changing the company's reputation:

> *"you get some very visionary leaders are thinking 'well actually it may be changing the perception of the company is very important'" - SC14*

This perception led the company to decide that it was:

> *"very interested in being a leader in the market - trying to pull those technologies together, so putting oil & gas and floating wind or wave or tidal together with - to deliver something now" - SC14*

---

[2] The Beatrice oilfield lies in the Moray Firth and became the site for the Beatrice offshore wind demonstration project (2 x 5MW turbines), and latterly the site for the Beatrise, Moray East and Moray West offshore wind farms

5.2.1.3 Entrepreneurial culture

In many cases, these entrepreneurial activities required a supportive culture within the organisation making this commitment. Organisational leadership was seen to be critical in this:

> *"[the CEO] wants all of his leadership team to be entrepreneurs. And anyone can come with an idea, anyone can come with a new business proposition. And they are encouraged…they are encouraged to be entrepreneurial and they get a lot of support to do that. It's not an individual entrepreneurship; it's a corporate entrepreneurship supported by a network. But it wouldn't happen without that leadership." - SC10*

Another theme which emerged in the discussions on entrepreneurial activities was the impact of competition on these activities. While SH40 said that *"competition is always a good thing"*, others recognised that the competition between actors could limit the scope for collaboration and thereby slow innovation:

> *"It's got very cutthroat between the utilities. They're not talking to each other as much as they were. And the supply chain is not talking to each other either…it's the same competitive issue." – SC14*

Finally, the point was made that the number of device developers in the wave and tidal stream sector was still very high, while the number of technology providers or OEMs in offshore wind had consolidated down to two or three, and this was seen to be a reflection of the relative maturity of the marine versus offshore wind sector. While some felt that diversity led to competition, and this was good:

> *"The fact there are a number of players in the marketplace has been super healthy for innovation" - SO77*

others felt that the diversity of developers and the failure to converge on an optimal design for wave or tidal was unhelpful:

> *"I think we're now in a stage of having probably too many individual technology developers doing slightly different things." – SO75*

Conventionally, one of the measures for entrepreneurial activities has been the number of participants. The recognition from the interviews that more is not necessarily better means that this metric should be interpreted with caution.

5.2.1.4 Differences between offshore wind and marine

Many interviewees referred to the headstart provided to offshore wind in the form of onshore wind technology and the consequent reduced requirement for early stage technological innovation and entrepreneurialism. The existence of viable onshore wind turbines, with a dominant three-bladed horizontal axis design, gave developers immediate confidence that moving offshore was likely to be possible, and that onshore turbines could be adapted and marinised to allow for offshore operation.

As a consequence, entrepreneurial activities in offshore wind have recently been most focussed on supply chain activities, such as mass production, foundation technologies, installation, operating and maintenance strategies, and financing and regulation:

> *"Obviously in the supply chain there has been grand commercial entrepreneurial behaviour" – MTD58*

In contrast, many noted that there was no dominant design in tidal stream or wave technology and that developers were essentially starting with a clean sheet of paper:

> *"I guess what wave and tidal stream didn't have was a kind of a precursor that people could relate to like the equivalent of onshore for offshore [wind]. So certainly for wave, they were starting from scratch" – SH40*

As a result, the sectors are at very different stages of maturity. In terms of Technology Readiness Level (TRL)[3], it is unarguable that offshore wind turbines up to 8-9 MW are at TRL 9, while tidal stream and wave technologies are far behind. As result, the kinds of organisations in each sectors are quite different:

> *"I suppose wave and tidal stream are very much characterized by small [and] medium sized enterprises. There are no really large OEMs involved." – SO77*

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[3] Technology Readiness Levels (TRLs) were defined by NASA as a nine-stage scale to assess development of new technologies. They are described in detail in section 8.2

At one stage, larger organisations appeared to be getting involved in the marine sector:

> *"We saw Siemens getting involved a few years ago through Marine Current Turbines[4], maybe even others. I think, as an observer, I would say, it felt like "okay this is a great move. This is what the sector needs" - SO75*

However, this was a short-lived trend, and these larger entities have progressively withdrawn from the sector, leaving it as PM55 described:

> *"However in my mind when it comes to wave, it is much more about smaller - what I would describe as maybe not even at SME levels - individuals almost who are trying to build a technology that at the minute isn't commercially viable" – PM55*

5.2.1.5 Impact of competitive pressures

A number of interviewees alluded to the link between entrepreneurial activities and the expectation that the TIS in which those activities were taking place would successfully emerge.

WPD1 captured this by noting that entrepreneurial activities were:

> *"driven by competition, and the technology that that competition is engendering." – WPD1*

A WTG manufacturer explicitly recognised that their customers looked over an extended time horizon in considering investment:

> *"Our customers are very sophisticated as you'd expect them to be when they're investing in billions of pounds worth of kit. So our customers will look at the discounted cash flow impact of lifetime cost and LCOE." – WTG15*

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[4] Marine Current Turbines Limited was a UK-based developer of tidal stream technology which successfully deployed two prototypes in the sea in North Devon and Northern Ireland. It was acquired by Siemens in 2012. Siemens sold it to Atlantis Resources in 2015.

Others also pointed to the importance of competition, whether within the sector (as referenced by SO32) or from other investment opportunities within the entity considering entrepreneurial activities within the TIS (as described by SH40):

> *"So now you're seeing more competition and that also drives more and more technology competition." – SO32*

"So BP invested a huge amount of money in offshore wind in the early days, and had a big team looking at it, trying to understand it, but they shied away actually and I think that was probably influenced by the oil and gas price and probably uncertainty around future subsidy regimes for offshore wind." – SH40

SH43 summed up the interaction between entrepreneurial activities and the emergence of the technology most succinctly:

> *"It's a chicken and egg situation. You won't have the entrepreneurs unless there's a genuine opportunity for them to exploit". – SH43*

5.2.2 Actors, institutions and networks

5.2.2.1 Actors

Actors contributing to this function included individual entrepreneurs (including technical and commercial entrepreneurs), researchers in institutions and corporate entrepreneurs. Critical supporting roles were played by funding bodies and industry bodies.

The type of entrepreneurial activity and the actors typically undertaking them were closely related, as shown in Table 5-1.

Type of entrepreneur	**Typical activities**	**Wind vs Tidal Stream and Wave**
Individual	"Inventor" – early stage technology development, initial fund raising (friends and family, grants), patenting	Dominates in wave and tidal stream; wind benefitted from onshore wind forebears. Main focus is technical.
Small corporate	Further technology development, early project development, fund raising	Early offshore wind projects were dominated by small corporates, which have now sold out

		to large corporates. Focus technical and commercial, regulatory framework evolving
Large corporate	Medium to large scale project development, refinancing	Entrepreneurialism by large corporates focussed on commercial, including refinancing through sale of interests to financial investors and development of supply chain opportunities
Support organisations	Funding support, facilitating joint projects, test centres (eg EMEC)	Support organisations dedicating support as appropriate to TRL, regulatory framework evolved
Government	Development of regulatory and licensing framework	Framework co-evolved with technology

Table 5-1: Types of entrepreneur and activities (author's analysis)

The emergence and motivations of these actors were attributed to a range of factors. They ranged from individual inventors working on an energy capture technology or ancillary system just because they wanted to show it could be done (WTG15), to large corporates devoting time and resource to entrepreneurial activity with the aim of building a leadership position in an emerging new sector (SC56), or because participation in the energy transition was seen as existential (SO60), and even in response to overt or subtle Government pressure (SO34):

> *"These were enthusiastic engineers, and academics in some cases, who just wanted to demonstrate that it could be done." - WTG15*

> *"Ørsted for example have been very much the entrepreneurial spirit in terms of the sector - put it this way, I don't think without Ørsted first mover advantage - I don't think we'd have been at £57.50/MWh [CfD strike price] today. If we didn't have a dominant market player of Ørsted's standing and vision." – SC56*

> *"I can see for the big established players that…unless you change your business model you might not be there." – SO60*

> *"There was real pressure from the Scottish Government on companies wishing to work in Scotland to take an interest in these emerging technologies" – SO34*

This is the first explicit example of interplay between the functions – Government pressure, or at least Government making its desires explicit, is a clear example of F4 – Guidance of the Search (see Section 5.5).

5.2.2.2 Institutions

Interviewees related that entrepreneurial activities involved a full range of institutions [87], including the "hard" institutions which provide support for entrepreneurial activities across the renewables sector and "soft" institutions such as the general cultural approval for entrepreneurial activities in the country.

"Hard Institutions"

Interviewees referred to a number of "hard institutions" which were considered to have been important in the emergence of offshore wind and the development of tidal stream and wave energy. These included the Carbon Trust's Offshore Wind Accelerator programme, other revenue support and grant programmes such as the Renewables Obligation and Contracts for Difference (SO32), UK and Scottish Government grant schemes and European grant support programmes (SO34).

> *"So you know at the beginning - we had grant funding. You know you could just you know get to a certain amount of grant and then you're helping to build a prototype or demonstration projects, then moving to this other market: the feed in tariff on this renewable obligation which is still providing enough certainty to make it attractive enough for you to invest." – SO32*

> *"They got a grant - they got some money" – SO34*

Additionally, the hard institutions around protection of Intellectual Property were described as important, particularly in the context of the competitive rivalry between technology and project developers:

> *"This is our IP: It goes right to the heart of our ability to differentiate." – WTG15*

"Soft institutions"

Interviewees described the importance of an entrepreneurial culture, particularly in the context of corporate entrepreneurship:

"It's not an individual entrepreneurship. It's a corporate entrepreneurship supported by a network. But it wouldn't happen without that leadership" - SC10

More widely, the wider social norms supporting entrepreneurial activities, and the societal recognition of a need for decarbonisation of the energy system have been important factors in the emergence of this sector. A recent book – "Energy at the End of the World" [146] describes the soft institutions in operation in Orkney as "Orkney Ltd". Orkney is a critical location for the development of tidal stream and wave technologies, as it is the home of the European Marine Energy Centre (EMEC) - a grid-connected and accredited test centre for wave and tidal stream energy generation technologies, used (as of March 2019) by 20 tidal stream and wave developers, from 11 counties and deploying 31 individual devices [147]. EMEC forms the nucleus of an informal network.

EMEC, together with the soft institutions described by Watts, are leading to collaboration across the archipelago to facilitate the development of tidal stream and wave energy. Watts describes how the culture is guides behaviours in Orkney, which she describes as being dominated by a culture of avoiding being "bigsy". She says:

"Expressing your personal opinion in public, raising your hand and speaking, is to stand above others and risks being seen as personal aggrandisement and bigsy. Personal opinions are expressed, but in a quiet word after the meeting, in the car park afterward, or in a chance meeting on the street." – Watts, page 227 [146]

This culture is one where entrepreneurial activities are enabled, and where creativity and self-determination are commonplace. She describes a local consultant and entrepreneur, Gareth Davies, seeking to rework the local electricity system:

"Rather than being dependent on the national grid and centralized electricity market, he proposes a self-determined, decentralized solution that is appropriate to the place: reconfiguring and reweaving the local energy network with what is to hand." – Watts, page 350 [146]

The soft institutions are clearly influential in enabling entrepreneurial activities, especially in the marine sector.

5.2.2.3 Networks

The existence of networks within the TIS was considered to be important, as through these networks entrepreneurs were able to communicate and collaborate:

"It's a corporate entrepreneurship supported by a network" – SC10

The leading formal network in offshore wind is the Carbon Trust's Offshore Wind Accelerator [148]– a joint industry project involving the Carbon Trust and nine offshore wind development companies (EnBW, E.ON, Innogy SE, Ørsted, Scottish Power Renewables/Iberdrola, Shell, SSE Renewables, Equinor and Vattenfall), which coordinates joint projects and "aims to reduce the cost of offshore wind, overcome market barriers, develop industry best practice and trigger the development of new industry standards". The Accelerator has coordinated a number of industry-wide projects, which are discussed further in the sections on Knowledge Development (Section 5.3) and Knowledge Diffusion (Section 5.4).

In the marine sector, the Carbon Trust was influential in funding the early work of the European Marine Energy Centre – the world's first accredited grid-connected test centre for wave and tidal stream technologies. This forms the hub of a network of marine energy technology developers, and produced the first standards for the marine sector – an important stage in the maturation of this sector:

"So in a more mature space…things like standards and standardisation are quite important and I suppose I see standards being the way of creating a sort of common language within a technology ecosystem" – SH40

Additionally, the looser networks rooted in the industry bodies RenewableUK and Scottish Renewables, and the industry specific groupings provide a linking architecture for actors in these technologies to collaborate. For wind, these networks are the Global Wind Energy Council, the European Wind Energy Association and the EU-supported European Technology and Innovation Platform on Offshore Wind.

At present, there is no clear industry voice expressed through a network body for tidal stream and wave. In the UK, one form of entrepreneurial activity being pursued by the leading tidal stream technology developers is the development of a Marine Energy Council, at which the actors can meet and define and implement an agenda for engagement with Government. This is seen as a critical step in making a coherent case for tidal stream to Government, in part as a response to Government's previously expressed frustrations with the former lack of a united and coherent message from the sector"

> *"I think…the biggest barrier to market formation is the fact that this industry – I'm talking about tidal particularly – do not speak with one voice." – MPD72*

Speaking about the Marine Energy Council and its engagement with Government regarding potential revenue support, one project developer said:

> *"I think getting people to agree that this is the system that they could all work within, also has the benefits to government - for them seeing that there will be a number of players in the competition." - MPD72*

Both formal and informal networks exist to help actors with entrepreneurial activities, and they are acting to address industry-wide challenges (e.g. the Offshore Wind Accelerator, Wave Energy Scotland), to talk to Government (e.g. industry bodies, the Marine Energy Council) and even to help build the legitimacy of offshore wind and marine renewables.

5.2.3 Metrics, indicators and drivers

Conventionally, as set out in Table 2-1, metrics for entrepreneurial activity include numbers of participants, numbers of experiments and numbers of startups. The interviews found that these were not necessarily always unambiguous, as it was felt that in the marine sector there might be too many bodies chasing too little funding support.

Indicators have been described as technology convergence, maturity of technology, entrepreneurial culture and availability of venture capital. Table 5-2 sets out the findings of this research in relation to metrics, indicators and drivers for offshore wind and marine, in the context of F1 – Entrepreneurial Activities.

Metric / Indicator / Driver	Offshore wind	Comments	Marine	Comments
Numbers of participants	3 major WTG OEMs	Industry has consolidated onto 2-3 major western manufacturers	Many developers	Very few well-funded technology developers
Number of technology experiments	Relatively few	Some experimentation in floating and in O&M approaches	Many different technologies	Very few technologies with any track record of performance
Number of startups	Few	Early stages of UK offshore wind generated startups (Warwick, Eclipse, SeaEnergy, Mainstream)	Many startups in both wave and tidal	Many startups but high failure rate
Technology convergence	Strong	Core WTG technology converged onto 3-blade horizontal axis axial flow upwind turbine	Very poor in wave; some convergence in tidal stream	Multiple devices concepts in wave with no clear "winner"; many different concepts in wave
Maturity of technology	Good	Well established technology, provided by well-capitalised large OEMs	Poor	As above, little convergence on dominant technology means limited resources for maturing
Entrepreneurial culture	Adequate	Culture of entrepreneurship was strong when it was required; sector now more mature	Good	Energetic entrepreneurial culture
Availability of venture capital	Good	Maturity of sector has moved beyond venture capital to more mature investment capital (eg insurance companies, pension funds)	Poor	Venture capital withdrawing from sector due to failure of earlier investments, unclear route to market
Engagement in demonstration projects	Some	Fixed offshore wind now "business as usual", demonstration of	High	Almost all technologies at demonstration stage

		floating now under way		
Acquisition of relevant companies	Some	Some consolidation of offshore wind OEM sector (eg Siemens acquiring Bonus, MHI/Vestas merger, Siemens/Gamesa merger	None	Very little. Atlantis acquired MCT (mainly for its sites), but no other acquisitions

Table 5-2: F1 metrics, indicators and drivers: offshore wind and marine (author's analysis)

5.2.4 Validity

The average score for F1-Entrepreneurial Activities (on the five point scale) was 3.67, with a standard deviation of 1.24, suggesting that the interviewees considered F1 to be both valid and important. The coding of all interviewees found extracts which were relevantly coded to Entrepreneurial Activities, with many comments referring to the motivations for entrepreneurial activities, including positioning the company competitively, changing perceptions of a company and ultimately making a profit. This was subjectively supported with interviewees using positive phrases such as:

> *"Encouraged to be entrepreneurs" – SC10*
>
> *"Very interested in being a leader" – SC14*
>
> *"Goes to the heart of our ability to differentiate" - WTG15*
>
> *"Huge need for entrepreneurism" – PM49*
>
> *"[Entrepreneurs] have been pretty critical" – MPD59*
>
> *"[Entrepreneurship is required to] remain a world leader" – MTD64*

The minimum score given was 1, by WPD7, who felt that the initial impetus to offshore wind in the UK was more developer-led than purely entrepreneurial:

> *"I never felt that there were huge numbers of entrepreneurial people doing what we were doing which was trying to be developers" – WPD7*

This emphasis on project development, rather than entrepreneurship in creating new technologies, may reflect the adoption and modification of existing onshore wind technologies, rather than a perception of a need for innovation of an entirely new technology. As such, the low score does not pose an outright challenge to the concept of this function, but more reflects this interviewee's perception of the importance of the "baked-in" entrepreneurism in the existing onshore wind technologies, and their view that the early stages in offshore wind in the UK were more about project development than technology innovation.

Finally, it may also be that the interviewee as an individual did not view themselves as an entrepreneur, although it is interesting that this respondent - WPD7 - was actually named by another interviewee - SC14 - as an example of an entrepreneur in the sector:

> *"There was (sic) innovators like [WPD7]…" – SC14*

Additionally, WTG12 also scored F1 – Entrepreneurial Activities as 1. This interviewee felt that the bulk of entrepreneurial activities, particularly in the field of WTG development – their core interest – had taken place outside the UK and been undertaken by large international companies:

> *"I would say that the industry has been entrepreneurial in terms of finding lots of technologies and ways to improve, but the core basis of the technology and the growth of the industry is largely founded on large foreign-owned companies." – WTG12*

On inspection, it is clear that the perspective of this interviewee was focussed on their own specific commercial interest – wind turbine development – but that they explicitly noted that the industry has been entrepreneurial in many areas.

5.2.4.1 Sectoral analysis

Figure 5-3 shows the average scores for F1 - Entrepreneurial activity by respondent group. All respondent groups scored the function at 2.5 or more, with Support Organisations and Stakeholders rating it as least important, and the technology and project developers and supply chain– those most likely to be engaging in entrepreneurial activities scoring the highest.

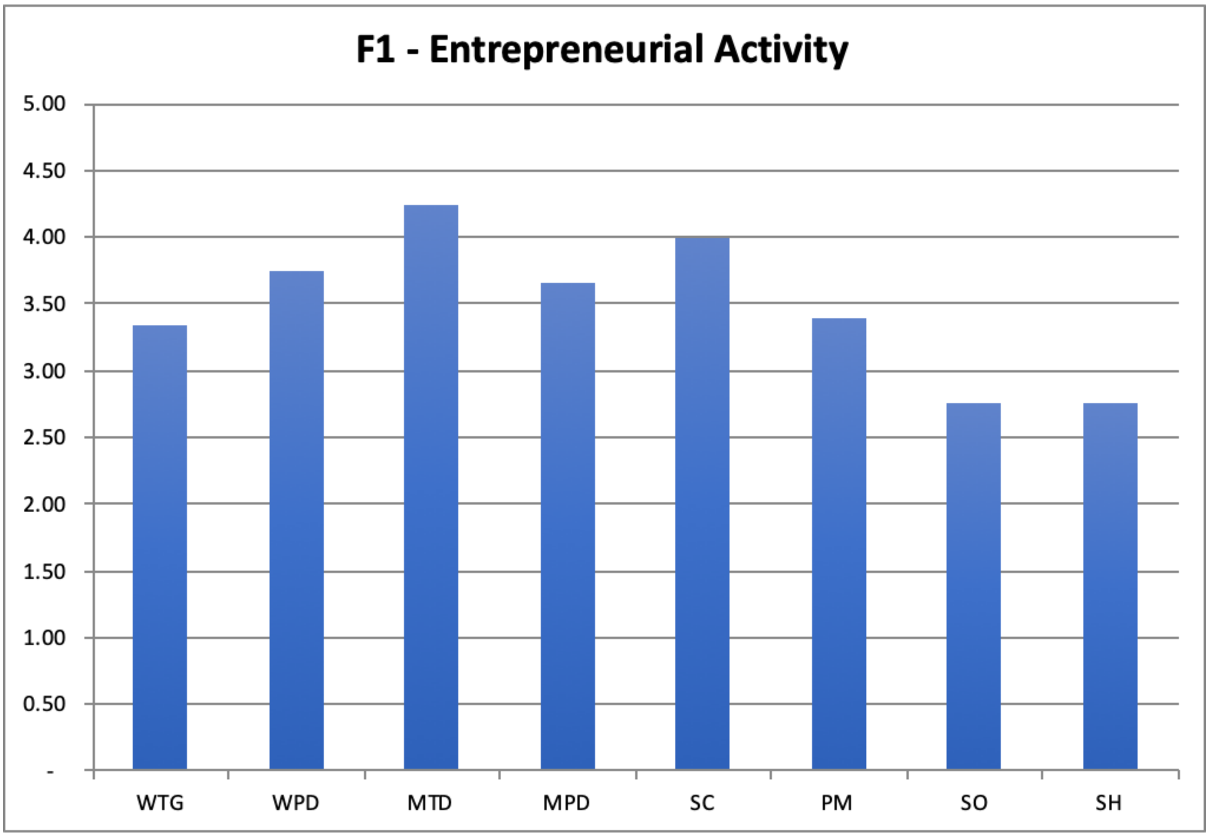

Figure 5-3: Analysis of F1 -Entrepreneurial activity by respondent group (author's analysis); Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

5.2.5 Conclusion – F1 – Entrepreneurial Activity

In conclusion, it is considered that the validity of this function is confirmed by the interviewees. Entrepreneurial activities were agreed to be a critical factor in the emergence of offshore wind. Offshore wind is now considered to be a mature sector, and the requirement for entrepreneurism has shifted to incremental innovation in WTGs, together with a focus on cost reduction and performance improvement through better installation, O&M and financing.

The marine sector was quite different. As an immature sector, it still has widely diverse technology types competing to be the type onto which the sector converges. Entrepreneurship remains important, as the sector seeks to identify viable wave and tidal stream designs.

Entrepreneurial activities as described by the interviewees include a wide range of activity undertaken by both individuals and corporate bodies: technological innovation (including wind turbine and tidal/wave generator design, prototyping and testing, design, fabrication and installation of ancillary systems); regulatory, support, funding and commercial innovation; creation of the environment in which there is a role for these technologies.

In offshore wind, entrepreneurial activities are less focussed on development of the generation technology than in the marine sector, as wind has been able to benefit from the earlier development of onshore wind generators.

5.3 F2 - Knowledge Development

"Innovation…is different to entrepreneurism" - MPD24

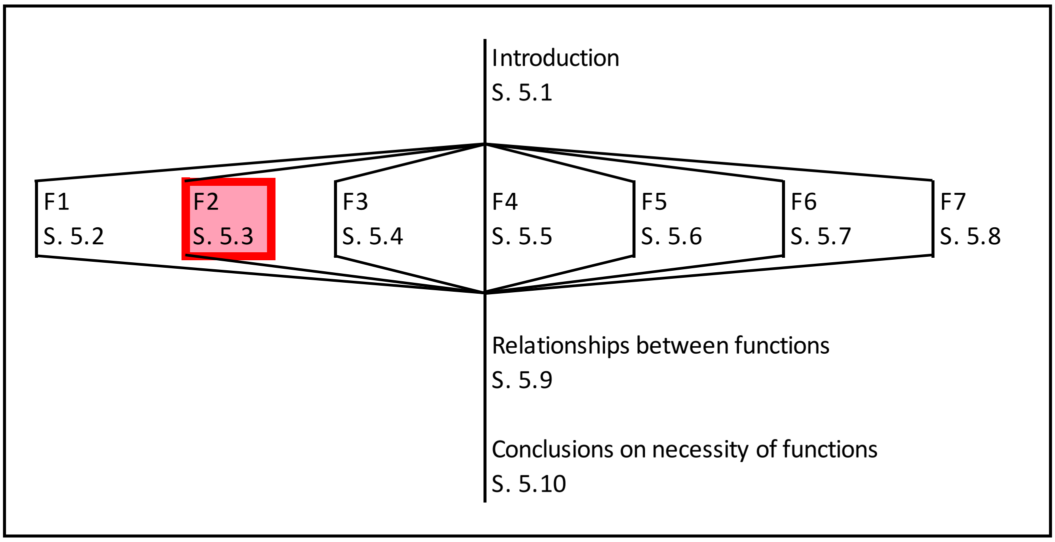

Figure 5-4: Section 5.3 roadmap

5.3.1 Key themes

Knowledge development was widely acknowledged among the interviewees as a critical aspect of TIS development. The interviews explored the subject of innovation from many directions and a number of key themes emerged. They included discussion of what was being innovated and the motivations for that innovation and knowledge development, the innovative progress made and yet to make, who was undertaking research and development, the relevance of oil and gas experience and some differences between offshore wind and marine, and finally it became clear that innovation was driven by competitive factors.

5.3.1.1 Subjects for innovation

Interviewees identified innovation in technology, commercial and policy making as being important for the emergence of offshore wind and marine. While there was a strong focus on technology development, this encompassed all technical aspects of the system, including turbines, foundations, installation and operations and maintenance. Different interviewees identified different foci for knowledge development – often reflecting their own specialism or interest:

"Look what happens when you make your turbines bigger" – WPD1

"There has been a lot of process improvement and 'leaning' of that process…we've got better lifting equipment, better offshore" – WTG12

"When I look at what we've done on offshore wind…nearly all of it has been developed by us on the job. We're mostly installing cables and foundations" – SC14

"There has been quite a lot of developments around the foundation side" – SO32

"A radical rethinking of the construction sites themselves – SO34

"A lot of the innovation that we're doing now is really around the fringes in offshore wind in reducing costs – such as optimising boat movements" – SH43

"Ørsted have really been trailblazers for the multi-contracting model" – SC56

"The question is – is there one more jump to come [in wind turbine capacity] and I don't know the answer to that…time will tell" – WPD7

"Commercial innovation as well" – SO74

5.3.1.2 Motivations

The motivations expressed for knowledge development were varied, and included the large-scale geopolitical momentum for green energy, response to Government funding policies, and the most commonly-stated motivation – the opportunity to develop a technology with the potential to generate profits.

Government policy was cited as a driver for R&D, as MTD22 agreed that government's structuring of R&D support and other support drove the knowledge development towards larger devices.

Market pull, or the prospect of making a return on investment, and the competitive setting and focus on profit it implies, was described by a number of interviewees as a strong motivating factor:

"R & D is still essential because as we are now in this sort of squeezing of cost in order to maintain it as the most competitive way to make electricity" – WTG15

"Clearly that strong market pull would have given RePower the confidence to invest in the 6MW platform. Same deal with MHIVestas, and you can imagine these turbine companies all playing leapfrog" – SH40

"The strive to gain a competitive advantage drives knowledge" – SC56

"I think the challenge is how do we make wind on par with other energy sources, and the true innovation has been in terms of the efficiency, the cost effectiveness of it, to make sure there is parity between that and other energy sources" – SO60

In one case, an interviewee combined these factors, recognising that government support, through funding mechanisms, was required to create a virtuous circle of cost-reducing innovation leading to increased deployment.

"I think the drivers all the time have been financial in the race to reach grid parity…huge innovation has been required, which has needed subsidy to reward developers" – WPD63

This commercial driver was repeated by another of the wind project developers:

"Cost reduction continues. It has to, and that's driven by competition and the technology that competition is engendering" – WPD1

5.3.1.3 Progress

Interviewees expressed a range of views on the degree of progress in innovation in offshore wind, tidal stream and wave. In all cases, further innovation is recognised to be required, even though offshore wind is already close to being a commercially viable technology in the context of the overall electricity system.

The most clearly-expressed area in which progress was described was turbine size, as this has been a strong driver of cost reduction in offshore wind. The first offshore wind farm, Vindeby, comprised 11 450kW turbines [48]. By the time of the first offshore wind deployment in the UK, at Blyth, turbine size was 2 MW. Turbines being installed in early 2019 are often 8-10 MW in capacity [48] and turbine manufacturers continue to compete to develop still-larger models:

"Turbine OEMs over the last 20 years have always had to leapfrog each other, in terms of product. And sometimes it was rating, sometimes it was rotor size depending on the market you're trying to address, but essentially that's a natural leap frogging process and GE has publicly announced that their next - their third - re-entry into the market will be with the 12MW Haliade. But don't make the assumption that the incumbents are not already ready to respond to that" – WTG15

"My perception is that in the UK the R&D for offshore wind and development of knowledge has come on leaps and bounds" - SC10

"What's changed of course over the past few years is that enormous cost reduction has switched offshore wind from being a 'niche but expensive with green' choice to actually being the cheapest way" – WTG12

It was recognised that knowledge development could arise both through academic research and through practical experience:

"Some innovation comes from R&D, some innovation comes from doing things" – SH36

"Learning by doing" – PM30

One observer noted that the momentum in learning could be lost or even reversed. This risk can be addressed through diffusion of knowledge, which is addressed in Section 5.4:

"And we just see this everywhere: that people and the industry are going back to square one – it's making the same mistakes that people before us made, that we made" – MTD58

5.3.1.4 Who is developing knowledge

A range of actors and networks were identified as developers of knowledge. These included industrial participants, universities, research institutes and industry support organisations. It was noted that the guidance of research and development in these organisations was not necessarily coordinated, as different funders had different R&D priorities. Some felt that the direction of innovation was determined by actors in the sector:

"The technology journey: a lot of that is driven by OEMs" – WPD1

Others considered that Government policy and funding priorities were more important:

"We're very good at putting money into universities and other organisations to develop technology and ideas. What we're not good at is the

industrialisation of that idea once it's been proven that technology works" – SC10

Some respondents felt that university-based research had offered little of value, and that industry had achieved more:

"I think, when I look at what we've done on offshore wind, very little of what has come from research institutes or universities and nearly all of it has been developed by us on the job…we're mostly installing cables and foundations and things like that, and most of the universities are focussed on things like how to improve the blades on turbines" – SC14

"So obviously R&D has played a huge role but it's not the R&D that I think government thinks it is - it's not a government sponsored R&D I don't think that's made a big difference and is responsible for the technological development. I think it's R&D within private enterprise." – WPD5

One interviewee felt that it was more important to be entrepreneurial than innovative, on the basis that innovation could be bought in:

"I think the entrepreneurial drive is a more important function. I think the knowledge side, whilst important, can be brought into the organisation" – MPD59

A number of interviewees also pointed out that the TIS is not meaningfully bounded within the UK, as much knowledge development had taken place, or continued to take place elsewhere:

"So the majority of our R&D still runs out of Denmark" – WTG 10

"A lot of the key pieces of R&D went on elsewhere" – SH43

5.3.1.5 Application of oil and gas experience

A number of interviewees identified that the experience of the oil and gas sector appeared to be directly applicable to the challenges offered by offshore wind and marine energy.

"And in the early days there was an expectation that that was just copy paste oil and gas technology." – WTG15

"[It] was my interest…to take all these skills we have from offshore oil and gas and actually do something in offshore renewables with skills that we have and the people that we have" – SC14

"We really like in offshore wind is the repetition – the fact that you can actually invest more in toolings and procedures, processes or methods, or bespoke stuff" – SC14

"So the difference between a Normally Unmanned [oil and gas] installation and a wind turbine is actually not that different" – SO60

However, it has become clear, at least to some interviewees, that the parallels were not as strong as initially hoped:

"And I think the experience is actually it's been anything but" – WTG15

5.3.1.6 Differences between offshore wind and marine

Inevitably, given their different levels of technological and commercial maturity, there were perceived differences between the state of knowledge development in offshore wind and the marine sector.

"With marine energy, with both wave and tidal, we're still trying to figure out what a turbine looks like and what size it should be. You know - what's the energy capture? Should you be going lots of small devices? Should you be going as few large ones as possible?" – SO75

In the marine space, innovation on basic device prototypes is continuing, although the lack of technological convergence, particularly for wave, was identified as a challenge in this sector. There has been some convergence in tidal:

"We've seen some consolidation of design around three bladed horizontal axis turbines" – SO77

In wave however, there has been little or no technological convergence:

"Wave suffers because there are too many parallel technologies, too many parallel solutions. We've probably got six or seven different types of machines and each one of those has probably 20 different people trying to pursue a solution with different fundamental physics" – SC14

5.3.1.7 Importance of cost reduction

Many interviewees noted that the development of knowledge was strongly focussed on cost reduction and realisation of market potential for the emergent technology:

> *"Cost reduction continues. It has to and that's driven by competition" – WPD1*

An appreciation of the potential future market size was seen to be a powerful driver for knowledge development:

> *"I think because of the size of the market and because of the visibility of the market going forward - the pipeline of work - I believe that in 10 years we would have moved on leaps and bounds and developed a lot more in the UK. And these could be foreign companies developing in the UK, but I'm confident that there will be a lot more engineering design development coming out of the U.K. - it may be foreign money that's pumped into it, perhaps with a bit of government support. But I have confidence that we will see an increase in R&D and building knowledge in offshore wind in the UK." – SC10*

> *"You need a very long term view of these things." – SC14*

5.3.2 Actors, institutions and networks

5.3.2.1 Actors

Actors contributing to this function included researchers in universities, research institutes and corporate research, as well as individual researchers:

> *"If we look in Scotland, which is probably one of the most productive environments in Europe for actually filing patents, only about 50 percent of those come from academia. 50 percent are people in their garages, with a great idea." – WPD63*

The funders for this support were widely recognised to be critical, and these included Government, government-funded entities and companies. The effectiveness of these forms of funding was open to question:

> *"So obviously R&D has played a huge role but it's not the R&D that I think government thinks it is - it's not a government sponsored R&D. I don't think that's made a big difference and is responsible for the technological development. I think it's R&D within private enterprise." – WPD5*

The types of knowledge development and the actors typically undertaking it were closely related, as shown in Table 5-3.

Type of knowledge development	Typical activities	Wind vs Tidal Stream and Wave
Individual	"Inventor" – early stage technology development	Inventors highly active in wave and tidal stream; little scope for individual innovation in wind
Supply chain actor	Development of knowledge through learning by doing	Supply chain strongly engaged in both wind and marine, with active learning by doing
Research institute	R&D activities often focussed on specific industry challenges	Active knowledge development in wind; limited activity by research institutes in marine
University	More general or "academic" (longer term) R&D	Wind OEMs forming partnerships with universities to address specific research agendas; less activity by universities in marine
Funding organisations	Funding support for R&D, test centres (eg EMEC)	Carbon Trust Offshore Wind Accelerator leverages industry funding to research industry-wide issues; Wave Energy Scotland funds research calls on fundamental and industry-wide agendas
Government	Funding support for R&D indirectly through revenue support for projects and by leveraging industry funding	Revenue support mechanisms fund projects which drive learning by doing

Table 5-3:F2 - Actors and activities (author's analysis)

Actors in the offshore wind and marine sectors play specific roles in knowledge development. The wide participation and range of roles in the delivery of this function confirms its validity.

5.3.2.2 Institutions

Both hard and soft institutions contribute to the development of knowledge.

"Hard Institutions"

Hard institutions overlap closely with the networks described above. Hard institutions include the ORE Catapult, the Carbon Trust's Offshore Wind Accelerator, Wave Energy Scotland, EMEC, the Marine Energy Council and many others. Their role is to facilitate knowledge development, by providing funding, intellectual resources, guidance and test facilities.

In addition, grant funding mechanisms structured to support the development of knowledge are examples of the hard institutions in place to support knowledge development. These range in size from the large EU Framework Programmes and Horizon 2020 programme, which can fund multi-million pound research projects, to the much smaller SMART awards, which are often focussed on single technology, small-scale innovation.

"Soft institutions"

The soft institutions which contribute to knowledge development include the body of Intellectual Property law, which acts to protect inventors, as well as a culture of knowledge development being valued in the UK. This culture is not without its problems:

> *"People tend not to look at the whole but solve one problem at a time." - SC14*

However, the coordinating effect of the hard institutions is seen to be positive for knowledge development and the development of the sector more generally.

> *"I think so, look at the Catapult report, with contributions from across the industry, and the industry is broadly aligned with what the Catapult is saying." - MPD59*

Watts [146] discussed the culture of knowledge development in Orkney:

> *"Being adaptable to changing circumstances, making and repairing things in ad hoc but effective ways, has a long island heritage" – Watts* [146]*, p 183.*

She quotes a local, making the point that this culture relies on a network of acquaintanceships across Orkney:

> *"As islanders, we make do…if you needed a spare part,* ***<u>you always knew someone who could make it,</u>*** *from tin, woodworking. We're practical" – Watts* [146]*, p 183, author's emphasis*

This cultural tradition, with its obvious benefits in an isolated community, informs how marine energy activities happen in Orkney. The network of cooperation enables knowledge development, and also (as discussed in Section 5.4) diffusion of knowledge.

In conclusion on institutions, it is clear that hard and soft institutions contribute to the development of knowledge.

5.3.2.3 Networks

The networks at work in knowledge development are those deliberately coordinated by a number of industry bodies. In wind, these include the Offshore Renewable Energy Catapult, the Fraunhofer Institute, the Carbon Trust's Offshore Wind Accelerator and others:

> *"There is a lot going on in the UK in terms of the ORE Catapult." – SH43*

In the marine sector, EMEC forms the nucleus of an informal network. More formally, the Marine Energy Council exists to coordinate the voice of the tidal energy sector in discussions with Government.

These networks are complemented by the informal networks of employees in these sectors, where movements between employers (which are frequently moves from developers to funders or vice versa) provide a valuable flow of information. This is explored further in Section 5.4, as part of the function of Knowledge Diffusion and Networking.

5.3.3 Metrics, indicators and drivers

Metrics for knowledge development, as proposed by Hannon et al. [97], Hekkert et al. [95], Darmani et al. [94] and Miremadi et al. [96] are summarised in Table 5-4. This table includes some comments inferred from the interviews on the relative levels of completion of this function by offshore wind and marine renewables.

The interviews revealed that the participants in the offshore wind and marine sector attributed little importance to these measures, preferring to emphasise the practical measures related to deployment. As Neil Kermode, the Managing Director of the European Marine Energy Centre, said in EMEC's statement following OpenHydro's liquidation:

"We know we just need to keep at it, keep getting metal wet, keep learning lessons from each other and those that have come before, and bring down the costs. This is the hard journey that all technologies have to travel." [149]

Metric / Indicator / Driver	**Offshore wind**	**Comments**	**Marine**	**Comments**
R&D projects	Wide ranging	Few formal R&D projects, but much innovation in the supply chain focussed on O&M, cross-industry requirements	Wide ranging	R&D projects mainly focussed on device development, array deployment
Patents	Patent count trend	Steadily increasing number of patents over time (see Section 5.3.3.1)	Patent count trend	Steadily increasing number of patents; many more in wave than tidal (see Section 5.3.3.1)
Investments in R&D	Significant	WTG OEMs in size race, as WTG capacity "leapfrogs"	Limited - focussed on device development and array deployment	Limited by financial capacity of developers
R&D strategies	Well developed	R&D strategies on cost reduction, operations and maintenance strategies	Focussed R&D strategies	R&D necessarily addressing issues of technical viability

Scientific publishing	Medium (see Section 5.3.3.2)	Literature includes techno-economic assessments, resource assessment,	Mixed: active in wave, limited in tidal (see Section 5.3.3.2)	Literature focussed on technical aspects of technologies
Learning rates	High	Transition from RO to CfD has driven cost reduction	Uncertain	Recent work by ORE Catapult [150] suggests potential for acceptable learning rates
Effort on technology development	Significant	Route to market well established, driving competitive technology development	Limited	Effort on technology development limited by funding constraints

Table 5-4: F2 metrics, indicators and drivers: offshore wind and marine (author's analysis)

As patents and scientific publishing provide some readily quantifiable insight into the level of knowledge development, these have been briefly reviewed for offshore wind and marine renewables in the following Sections 5.3.3.1 and 5.3.3.2.

5.3.3.1 Patents

Google Patents [151] provides an indication of the intensity of patenting activity. Counting the numbers of patents by year, based on key word searches, gives some idea of the relative patenting activity in each sector. The search criteria used here were "wind energy", "offshore wind", "tidal energy" and "wave energy". Figure 5-5 shows the numbers of patents returned by a Google Patents search for each of these key word combinations from 2000 until 2017 (the last year for which full data is currently available).

It is clear that the number of patents in all areas rose fairly steadily throughout the period (although there were a one-year trend reversal in "offshore wind" from 2012-2013 and "wind energy" from 2013-2014). It is notable that the number of patents in wave energy far exceeded that in either of "offshore wind" and "tidal energy" and the reasons for this are not immediately clear. This might be an interesting area for further research but is outside the scope of this work.

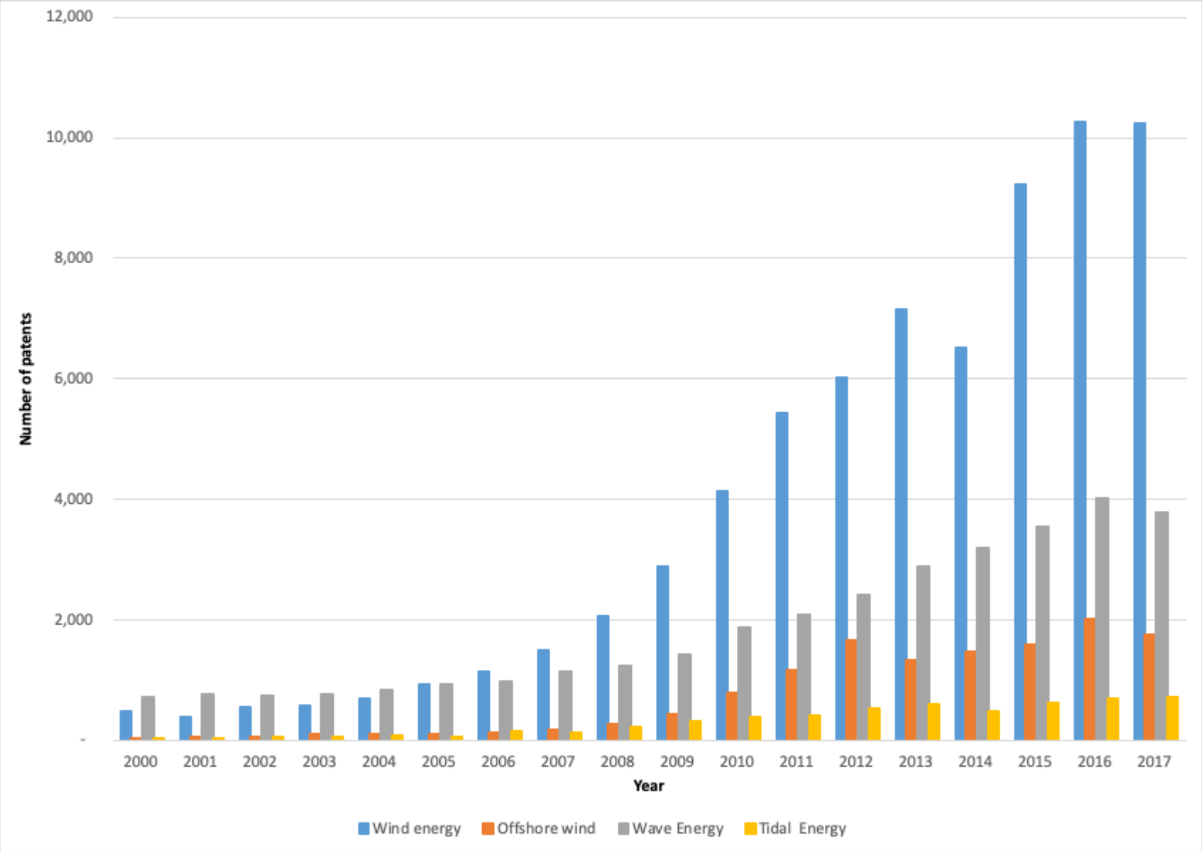

Figure 5-5: Patent count (author's analysis, [151]*)*

5.3.3.2 Academic publications

Science Direct [152] provides an indication of the intensity of academic research. Counting the numbers of articles by year, based on key word searches, gives some indication of the relative intensity of research in these areas. Figure 5-6 shows the levels of academic research between 2000 and 2018, using key words of "wind energy", "offshore wind energy", "tidal energy" and "wave energy".

The broad pattern is similar to that for patents shown in Figure 5-5, showing a steady and continuous rise in publication activity with wave energy activity far exceeding either of offshore wind or tidal.

This analysis is not intended to be authoritative, but rather to provide an indication of the levels of academic research activity.

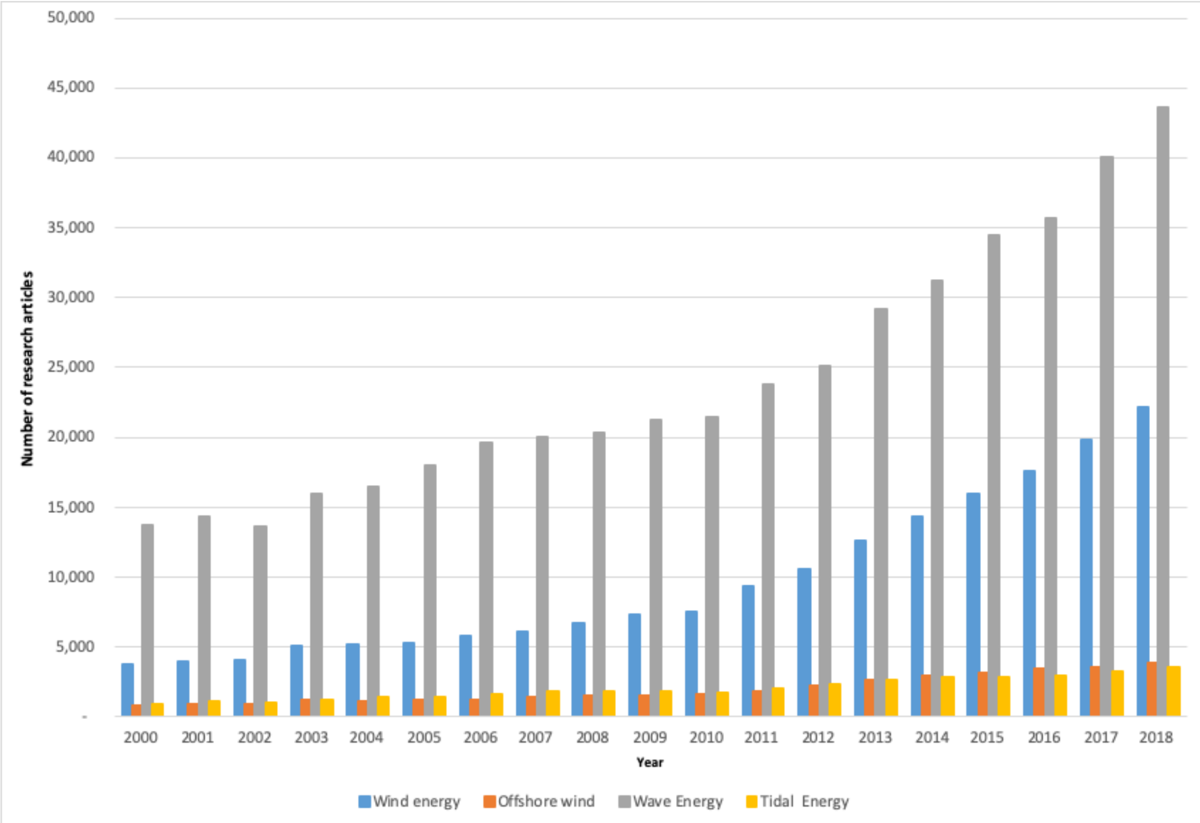

Figure 5-6: Numbers of research articles, 2000-2018 (author's analysis)

In both patenting and academic research, levels of activity in wave energy far exceed those in offshore wind and tidal. The reasons for this might be an interesting area for further research, and may be related to the perceived potential of wave energy coupled with the wide diversity of proposed technological solutions.

5.3.4 Validity

The validity of the function of knowledge development is clear. The mean score was 3.92 with a standard deviation of 0.97 (the lowest standard deviation found in the research). The lowest score was 2 (the highest low score found in the research), again supporting the validity of the function.

The subjective comments from many interviewees also supported the validity of the function:

> *"Research has been a big thing and remains a big thing" – WPD1*
>
> *"R & D is still essential" – WTG15*

"I think that R&D and knowledge development, from what I've seen, is critical" – PM29

"A lot of development happened, a lot of R&D, a lot of R&D spending" – SO32

"So obviously R&D has played a huge role" – WPD5

"Huge innovation has been needed" – WPD63

"For offshore wind, it's absolutely essential" – SO74

The lowest score for F2 – Knowledge Development was 2, received from SC14, SC20 and PM65 (in relation to tidal stream only). SC14 felt that "organised" R&D, undertaken by research institutes or universities had been of limited value:

"I think, when I look at what we've done on offshore wind, very little of what has come from research institutes or universities, and nearly all of it has been developed by us on the job" – SC14

"I think…either the projects or the contractors have had to solve the problems of how to do things" – SC14

What SC14 did not recognise was that learning by doing, as demonstrated in his view by the supply chain, is as much knowledge development as "formal" research. He was, in fact, supporting the validity of the function, as manifested through learning by doing.

SC20 admitted to a knowledge gap in this area, but felt that much relevant R&D had come from the oil industry:

"I mean the technical side of it isn't my forte, but…some of it, from an R&D and manufacturing perspective, comes out of the oil and gas industry" – SC20

This observation is reasonable, but it overlooks a great deal of innovation and R&D that has taken place in the offshore wind, tidal stream and wave sectors.

5.3.4.1 Sectoral analysis

Figure 5-7 shows the average scores for F2 Knowledge development by respondent group. Knowledge development was rated most highly by marine technology developers – who are currently very strongly engaged in this activity as they evolve technologies from prototype to commercial. It was expressed least strongly by the supply chain, which is inferred to be focussed on delivering existing solutions, rather than innovating new ones.

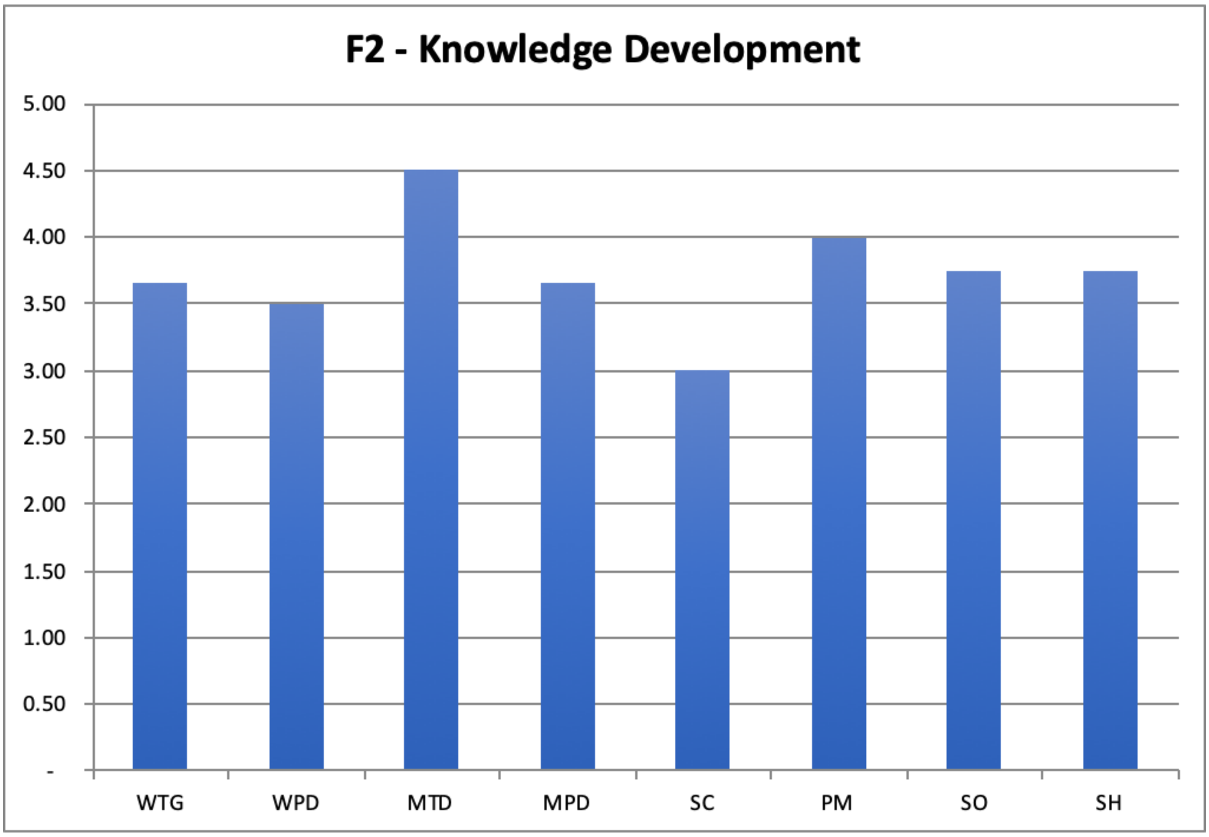

Figure 5-7: Analysis of F2 – Knowledge development by respondent group (author's analysis) ; Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

5.3.5 Conclusion – F2 – Knowledge Development

In conclusion, there is strong support for the validity of F2 – Knowledge development. The development of knowledge was widely recognised to be critical to the emergence of the TIS. Although offshore wind was seen to have benefitted from earlier development of onshore wind technology while marine technologies were at an earlier stage of development as they had to start from first principles, actors in both sectors agreed that the development of knowledge was an essential part of the process of emergence.

Knowledge development, as described by interviewees, was mainly considered to be the processes of industrial research and development. Although Universities and research institutes were seen to play a part, the main effort in relevant R&D was considered to be that undertaken by OEMs and the supply chain.

In offshore wind, it was seen that increasingly research and development are addressing questions of operational efficiency, including operations and maintenance, as well as upscaling of the core wind turbine technology from less than 1 MW in the first offshore wind farms to 10 MW turbines being commercially available.

F2 – Knowledge development has a strong link with F3 - Knowledge Diffusion and Networking, and this is explored in Section 5.4.

5.4 F3 - Knowledge Diffusion and Networking

> *"I think the developers and the suppliers are still willing and keen to share, because I don't think any of them have a golden bullet out there that is the ticket to success" – PM49*

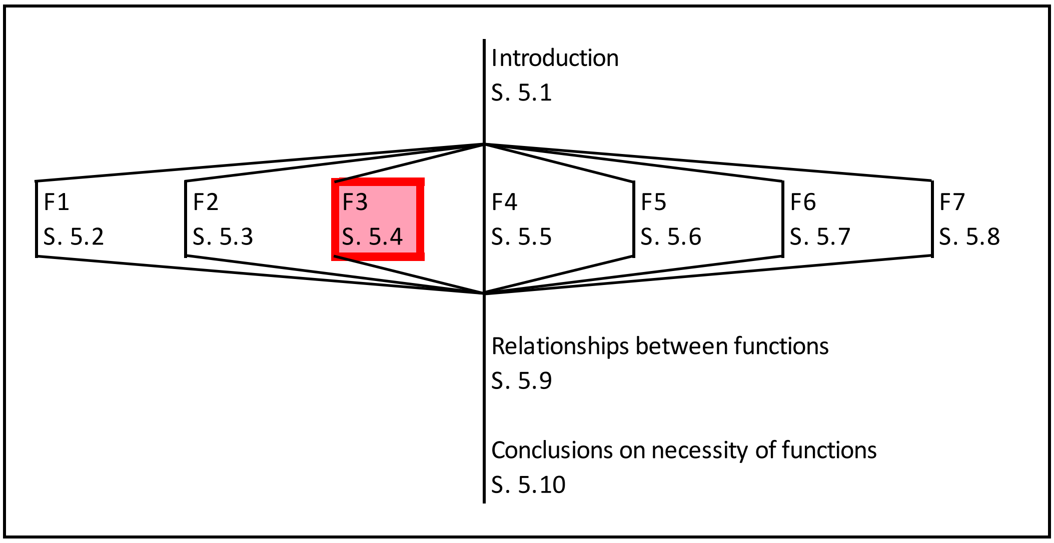

Figure 5-8: Section 5.4 roadmap

5.4.1 Key themes

The diffusion of knowledge and networking was widely agreed amongst the interviewees as an important factor in the emergence of the TIS. Although its importance was agreed, there were divergent views on the degree to which the diffusion was taking place.

The strongest key theme which emerged was the tension between the benefits for a company of maintaining confidentiality in relation to competitively-important IP and the benefits to the industry of sharing it. Other themes included

- discussion of the areas in which collaboration was taking place and how that collaboration was facilitated
- the importance of standards and the role of networking in their development
- the role of movement of personnel in achieving diffusion of knowledge, and
- the relationship between collaboration and competition.

5.4.1.1 Tension between sharing and confidentiality

The tension between the benefits to individual companies of keeping IP confidential and the benefits to the wider industry was a theme discussed by a number of interviewees. Some technology and project developers made the importance of their IP clear:

> *"There's no doubt we have technology that gives a competitive advantage that we don't share with anyone: - WPD1*
>
> *"As soon as you disseminate that knowledge in the market you haven't got the intellectual property any more." = MTD22*

The supply chain had observed this issue:

> *"I think the offshore renewables sector is the worst place I've ever seen for non-disclosure agreements. Nobody will talk to anybody without a non-disclosure agreement." – SC14*

Two policy makers also noted this tension:

> *"I guess the question is that balance between IP vs. what's in the best interests of the industry." – PM29*
>
> *"It's not clear that it is necessary for there to be diffusion of knowledge in the offshore wind market now, because you've got all the competitive reasons for that not to take place." – PM30*

A support organisation interviewee expressed the tension more pithily:

> *"Well, if they've come up with anything that they think will reduce the costs and that makes it more competitive, they're not going to tell anyone else, are they?" - SO37*

Although this tension was clearly expressed and widely recognised, it was also found that there were areas of collaboration where progress was being made.

5.4.1.2 Competition versus collaboration

Section 5.4.1.1 detailed the tension between sharing of knowledge and protection of intellectual property. The shift in the UK's revenue support regime for offshore wind from the Renewables Obligation, which was effectively capacity-unlimited, to the Contracts for Difference (CfD) scheme in which available capacity is limited, has drastically increased the competitive pressure on offshore wind farm developers seeking to secure new, funded capacity.

This was noted by a number of interviewees as having reduced the desire to share knowledge across this sector:

> *"The space in which we can collaborate as an industry has changed because of competition" – WPD1*
>
> *"My expectation would be that the movement from ROCs to CfDs would result in a significant reduction in the willingness to share any information to share knowledge." – WPD5*
>
> *"If you're competing against another for a finite resource or a CfD, you're not necessarily going to transfer the knowledge." – SC56*

The impact of changing revenue support systems, defined by F5 – Market Formation, on other functions is important, and explored further in Section 5.6.

5.4.1.3 Areas of collaboration

Although interviewees focussed heavily on the competitive tension for industry participants in sharing knowledge, they did recognise that there were areas in which it was possible. One important area of collaboration was through the Offshore Wind Cost Reduction Taskforce, which was formed to respond to Government pressure for reductions in offshore wind costs:

> *"The Cost Reduction Task Force really got industry working together. We've got the Offshore Wind Industry Council which comprises all of the developers and the key OEMs working together with dialogue with Government" – WTG12*

Other areas of collaboration addressed shared industry challenges such as environmental survey methods, and health and safety:

> *"We have done a lot of projects on floating LIDAR" – SO32*
>
> *"Offshore wind safety, and in other areas where companies don't compete, there's more appetite to share" – SH43*

Certainly, the benefit of collaboration was recognised:

> *"If you work together you will accelerate the commercialisation of the technology." – SO32*

5.4.1.4 Coordination of Collaboration

The benefits of collaboration were widely felt to be worth pursuing, and the interviewees talked about the entities which helped collaboration to take place. In addition to the Cost Reduction Task Force, interviewees cited the Crown Estate, Universities, consultants and Government-sponsored bodies such as the Offshore Wind Industry Council:

> *"Crown Estate…played a very important role" – SO34*

> *"the likes of DONG and SiemensGamesa getting together with a group of Universities" – SC20*

> *"Probably the best approach that I've experienced, which is still far from perfect in terms of outcomes, is the Energy Technology Partnership (ETP), based at the University of Strathclyde. Through this organisation, the 12 Universities in Scotland who engage in significant energy research bring their thoughts together and jointly support a programme of PhDs" – WPD63*

> *"In the operations space, a lot of contractors use consultants – they are a great way of spreading best practice" – SH43*

> *"There are governmental organisations – the Offshore Wind Industry Council, run by the UK Government and all the developers sit on that, and they do get as far as agreeing what R&D priorities are." – SO37*

Establishing these collaborative activities was clearly not easy, but the benefits, especially in terms of securing the "Offshore Wind Sector Deal" [47] announced in March 2019 were seen to be valuable:

> *"With a lot of work and co-ordination, industry participated in the cost monitoring framework" – SO75*

> *"The Sector Deal is a really important moment for the industry to find new ways to work together in areas of technology regulation and policy, where it makes sense for us to collaborate rather than compete" – WPD1*

> *"And part of that is a commitment from the developers to all contribute towards funding supply chain growth. So they are not only sitting around the table and talking they're working collaboratively on kind of industry*

solutions and are being prepared to commit funds to a kind of industry good pot." – WTG12

5.4.1.5 Standards

Standards were described as a sign that a technology sector was maturing and were considered to help drive costs down:

"I think, things like standards and standardisation are quite important and I suppose I see standards being the way of creating a sort of common language within a technology ecosystem." - SH40

"We can help drive standards but we can also point out where efficiencies can be made in the process. And I think as long as they benefit everyone, as long as we're not revealing privileged information, then I think we can play a role" – SH40

"The more standardization you can get earlier, the more shared learning there will be, the more progress rate will make down the cost curve" - SH40

"We'll get cheaper through standardisation." – MTD64

"I think standards play a really important part." - SO77

"I think we've got to be careful that we don't try and drive standardisation too quickly and to some extent we've got to let the market decide." – SO77

5.4.1.6 Processes of collaboration

Interviewees referred to formal and informal processes of collaboration. Formal collaboration, such as that undertaken by the Cost Reduction Task Force, involves formal agendas, scopes of work and specified aims. Informal collaboration and informal diffusion of knowledge is much less obvious, but is probably at least as important in enabling the transfer of knowledge among actors in the TIS.

Processes of informal knowledge diffusion include the transfer of staff between entities in the sector:

"There is clearly mobility across these companies…and that pushes the sector on, because you're taking the best in class knowledge and putting it into a new environment where it's expected to deliver" – SH40

"Knowledge diffusion is a natural consequence of the expansion of activity in the industry and mobility of personnel." – SH43

Informal networks are also critical. SH36 agreed that there was much to be learned in bars in Stromness, home of EMEC. PM30 put it similarly:

"I mean some of the best knowledge sharing was more informal and it's because a lot of this was done in Orkney." – PM30

5.4.1.7 Knowledge diffusion and competition

The diffusion of knowledge and networking are influenced driven by the competitive environment faced by stakeholders in the technology sector.

The interplay between the competitiveness in the offshore wind sector, which was significantly increased following the change from the Renewables Obligation to the Contracts for Difference system, and collaboration within it, was noted by a number of interviewees:

"The space in which we can collaborate as an industry has changed because of competition." – WPD1

5.4.2 Actors, institutions and networks

5.4.2.1 Actors

Actor	Typical activities	Wind vs Tidal Stream and Wave
OEMs and Supply Chain	R&D focussed on specific commercial needs	Intense competition for CfDs limits offshore wind collaboration; marine knowledge sharing limited by need to retain IP
Universities and Research Institutes	Generic R&D and research specified by industry partners	"Academic" R&D on offshore wind is largely guided by industrial partnerships, while on marine it is likely to be more fundamental
Government and other funders	Provision of funding routes (see Section 5.6) and setting of policy objectives (which can lead to knowledge diffusion, as	Funding route for offshore wind much clearer than for marine, especially following

	with Cost Reduction Task Force, see Section 5.5)	Offshore Wind Sector Deal
Consultants and employees	Informal transfer of knowledge around the sector	Offshore wind employs many more than marine, making potential for diffusion greater

Table 5-5: F3 - actors and activities (author's analysis)

Actors in offshore wind and marine sectors take specific roles in the diffusion of knowledge which may be either formal or informal. The interviewees strongly expressed a recognition that diffusion of knowledge and networking were beneficial for both sectors, but that achieving diffusion of knowledge was challenging, and impacted by other factors. In particular, the competitive environment was seen to be a strong factor limiting scope for collaboration.

5.4.2.2 Institutions

Hard and soft institutions are at work in diffusion of knowledge and networking.

"Hard Institutions"

The hard institutions active in knowledge diffusion and networking in offshore wind and marine renewables include those bodies specifically set up for the purpose, including the ORE Catapult, the Carbon Trust's Offshore Wind Accelerator, EMEC, and Wave Energy Scotland.

These networks provide a framework through with actors in the sector can collaborate, and were cited by multiple interviewees:

"If we look at the ORE Catapult, we've got the Offshore Wind Innovation Hub which is looking at technology roadmaps, strategy roadmaps for offshore and looking at what are these cross-sector issues… a body that's going to convene and pull academia in and a bit of joint industry stuff to actually solve these" – SO75

"I can give you a really good example: BEIS and the Industry established a joint initiative called innovation hub. So this is industry working together to advise both government and academia on the kind of technology and innovation priorities for the industry. The group has had great support from across the industry; all the technical people from those groups are involved." – WTG12

Additionally, across both sectors there are many conferences at which both formal and informal networking takes place:

"In the last 6 or 7 years, there has been a large explosion in conferences, the number of initiatives to get people to share and work together." – SH43

In some of the early leasing rounds for offshore wind, formal joint ventures were agreed between developers [48]. This adopted a strategy common in the oil sector, in which operators form JVs to explore and develop oil projects, thereby reducing their exposure to individual projects. These JVs would require sharing of technical information between partners, thereby driving some diffusion of knowledge.

Additionally, some funding mechanisms require collaboration and knowledge diffusion. For example, the author was involved with a UK-based project which was combined with a Swedish-led project under the European Union Sixth Framework Programme, with combination expected to deliver broader results, with better collaboration and at lower cost [153].

"Soft institutions"

As with the development of knowledge (see Section 5.3), the diffusion of knowledge also relies on a culture of sharing. As discussed in Section 5.4.1.6, the culture of sharing across the informal networks in marine energy is strong. Laura Watts [146], describes this culture:

> *"The Orkney marine energy industry is a global nexus where developers from around the world come together. At the EMEC test site they have to learn how to operate at sea together". Watts, p.336*

Anecdotally, in offshore wind, very deliberate steps are taken to counteract these soft institutions, by emphasising the commercial sensitivity of some information (such as CfD bid prices) to ensure that this critical information does not leak. As SH36 said:

"Sharing is the absolute ideal: you share lessons learned earlier, and everything accelerates faster. The problem is people don't always have the time or will." – SH36

5.4.2.3 Networks

Both formal and informal networks are at work in relation to diffusion of knowledge. Formally, networks included Government-sponsored entities such as the Offshore Wind Cost Reduction Task Force, the Energy Technology Partnership (a collaboration between Universities) and relationships between some OEMs and Universities with specific scope. For example:

"It's back to ORE Catapults, the Offshore Wind Accelerator - I think there's a big role for these guys to possibly be a bit more powerful in terms of the knowledge diffusion." – SC56

"The likes of DONG and SiemensGamesa getting together with a group of Universities and some grant funding to look into the challenges facing turbine " – SC20

Informal networks, such as the marine energy community and the renewable energy academic community, are also important in driving the sharing of knowledge through the sector:

"There's any number of parties that have come together that have a knowledge base, and that brings together largely I suppose the R&D and academic community alongside commercial enterprise." – SC20

5.4.3 Metrics, indicators and drivers

Metric / Indicator / Driver	Offshore wind	Comments	Marine	Comments
Numbers of workshops and conferences	Many conferences and reported recent increase in number	Interviewees reported continuing increase in number of conferences	Some conferences, but stable numbers	Well established "circuit" of marine conferences
Numbers of press articles	Steady increase to plateau, recent	See Section 5.4.3.1	Lower level than wind; steady increase to	See Section 5.4.3.1

	slight decline		plateau, recent slight decline	
Network size and intensity	Well developed network, global	Recent Offshore Wind Sector Deal includes commitments on job creation. UK developers increasingly developing internationally too	Poorly developed, localised to Orkney (and possibly Bay of Fundy, Canada)	Limited population, limited finance and poorly developed supply chain (except in Orkney) limit scope of network
Scenario / fore-sighting projects	Sector Deal	The Sector Deal [47] involved foresighting and scenario development	ORE Catapult report on cost trends for marine energy [150]	ORE Catapult report explicitly assessed development scenarios for tidal stream and wave
Existence of societal networks	Well developed	Offshore wind already employs 7,200 [47]	Poorly developed, localised to Orkney (and possibly Bay of Fundy, Canada)	Estimate on the order of 250 employed in marine in UK[5]

Table 5-6: F3 metrics, indicators and drivers: offshore wind and marine (author's analysis)

5.4.3.1 Press articles analysis

As the number of press articles is readily available, and provide some readily quantifiable insight into the level of knowledge diffusion, these have been briefly reviewed for offshore wind and marine renewables in the following Section 5.4.3.1.

Using LexisLibrary, the numbers of press articles in the UK press has been analysed, using key words “offshore wind”, “wave energy” and “tidal energy”.

[5] Estimate based on number of UK based wave energy and tidal stream energy devices, most with <5 employees, plus 5 leading (Atlantis, EC-OG, Orbital, Minesto, Wello) with an estimate of 10 employees each, plus 20 staff at each of EMEC, Wave Energy Scotland, ORE Catapult, the Crown Estate, UK and Scottish Government and supported by typical conference attendance of <100.

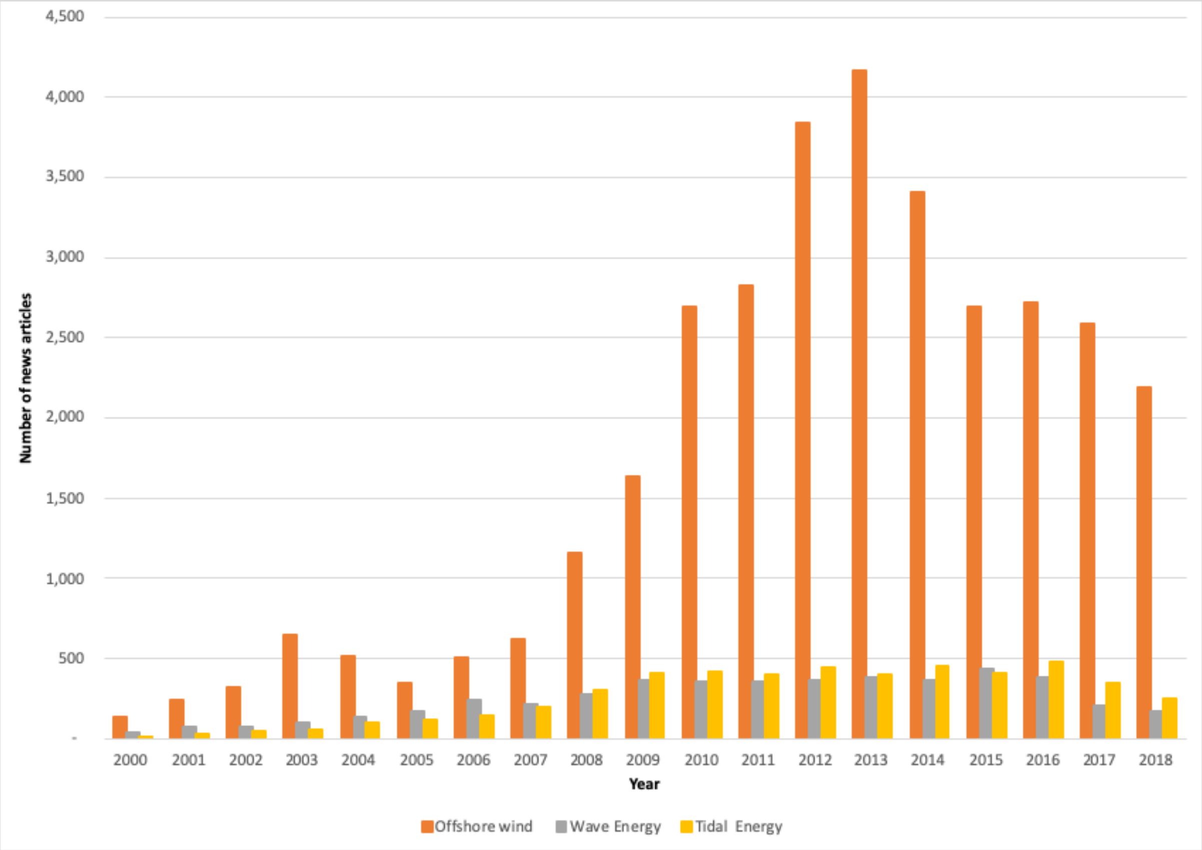

Figure 5-9: Press articles analysis (author's analysis)

Figure 5-9 shows this analysis. It is clear that offshore wind dominates in the press, increasing rapidly from 2007 to 2013/14, peaking at around 4,000 articles in 2014, before beginning a decline in appearances. Tidal and wave energy followed a similar pattern, but at a lower level, reaching around a peak of 500 articles each per year from 2009 to 2016.

It is speculated that the drop off in mentions of offshore wind is due to its becoming a routine part of the energy system, whilst interest in tidal and wave may have flagged due to the lack of success in these technologies.

5.4.4 Validity

The average score for F3 – Knowledge Diffusion and Networking was 3.35, with a standard deviation of 1.15. This makes it the lowest score of the seven functions reviewed but is nonetheless a score comfortably above the median point and strongly supports the validity of the function.

Some of the subjective wording used in support of the function was:

> *"The siting of offshore wind turbines in an array has benefitted from that sort of mid-TRL collaborative research" WPD1*
>
> *"It seems to me that as an industry it will only work if there is a market drive to make sure there is a sharing of all this knowledge" – SC10*
>
> *"I think these collaborative R&D programs have actually been quite fundamental." SO32*
>
> *"So people will move for a variety of reasons to different companies. And that kind of knowledge transfer is important." – SH40*
>
> *"So, yes, I think the sharing of knowledge is very important to ensure that the industry progresses at a more rapid rate." - PM49*
>
> *"It's absolutely key to any sector, I think, is knowledge diffusion." – PM55*
>
> *"Things like the Offshore Renewable Energy Catapult for example are, in my view, very very important." – SC56*
>
> *"I think it's extremely important.: - MTD64*
>
> *"It's absolutely essential." – SO77*

The lowest score for F3 was 1, given by WPD7 and PM30.

This was despite WPD7 referring to the importance of:

> *"Experience from other places of what you can do…it's how the transfer of knowledge comes" – WPD7*

PM30 seemed to give a low score for F3, as they felt that there is a time when collaboration is feasible and helpful, and other stages in the development when it may not be possible:

> *"So I think that it's not clear that it is necessary for there to be diffusion of knowledge in the offshore wind market now, because you've got you've got all the competitive reasons for that not to take place." – PM30*

5.4.4.1 Sectoral analysis

Figure 5-10 shows the average scores for F3 – Knowledge diffusion and networking by respondent group. Only Wind Project Developers scored this function below 2.5 (the scale mid-point), potentially reflecting the intense competition in this sector, and the reluctance to share information between developers. The function scored highest among Marine Project Developers (MPD), with other respondents presenting broadly similar scores between 2.5 and 3.5.

The higher score among Marine Project Developers may reflect the current interest in the marine community with developing a collective voice for discussion with Government, and a lobbying effort to secure targeted financial support for this sector.

Among other respondent groups, the low scores (in comparison with other functions) may reflect the competitive pressures and their impact on the potential to network and share knowledge, discussed in Section 5.4.1.2).

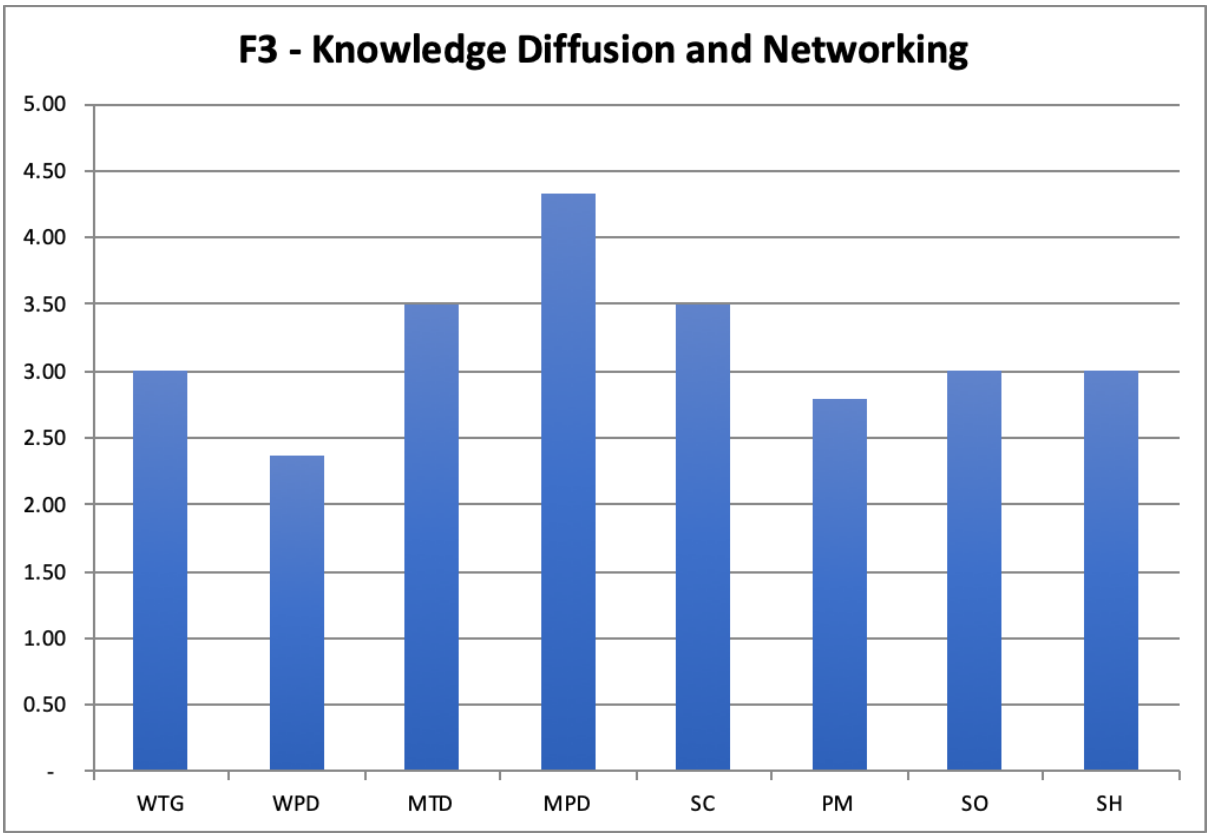

Figure 5-10: Analysis of F3 – Knowledge diffusion and networking by respondent group (author's analysis) ; Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

5.4.5 Conclusion - F3 – Knowledge Diffusion and Networking

In conclusion, the interview data provide strong support for the validity of F3 – Knowledge Diffusion and Networking.

5.5 F4 - Guidance of the Search

> *"General signals were that governments globally were going to be supportive of renewables as long as they could show a path to being subsidy free" – MPD24*

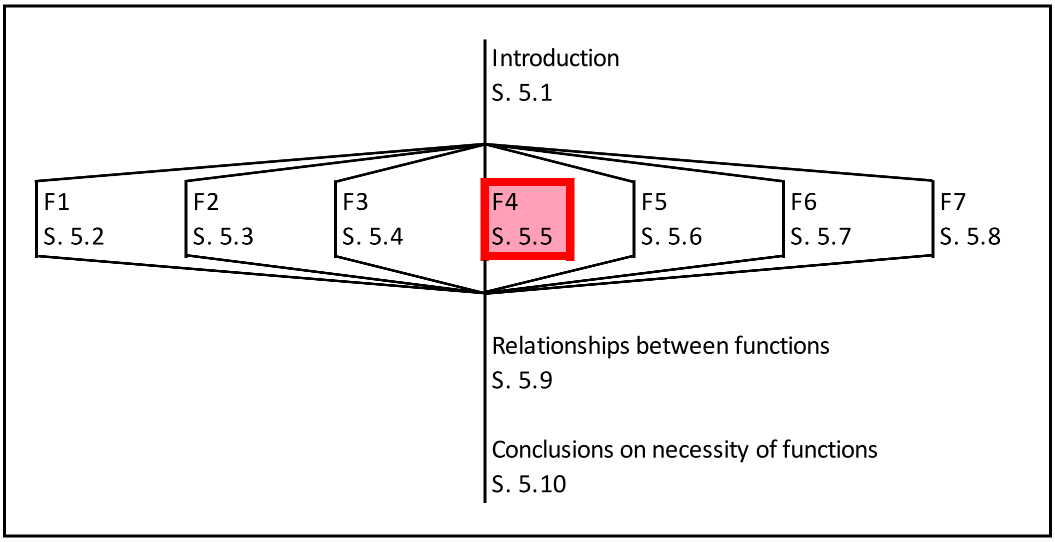

Figure 5-11: Section 5.5 roadmap

5.5.1 Key themes

Guidance of the search and the setting of policies in support of the development and deployment were universally seen to be critical in the evolution of the TIS.

The dominant key theme was the role of government, which included questions of government's motives, what government could do, the importance of policy, the constraints on policy (the "energy trilemma"), and the competence with which government executed these decisions. Other key themes were

- the importance of stability in policy direction
- the impacts on business of policy choices and how business could influence policy
- the risk of going "too big, too soon", and
- the effect of subnational governments.

5.5.1.1 Government policy

Claire Perry, Minister of State for Energy at the Department of Business, Energy and Industrial Strategy replied to a letter from the researcher asking about Government policy in relation to renewables, and specifically tidal stream and wave. In this letter [154] (which is included as Appendix 2), she pointed to the Government's support for renewables:

She focussed on the offshore wind success story:

> *"Through our policies we have massively increased our deployment of renewable generation. Renewable electricity now makes up almost 30% of our generation. Our renewable capacity has quadrupled since 2010 and the Contracts for Difference (CfD) auction prices of offshore wind have fallen from £114 per MWh to £57.50 per MWh within two years." – Claire Perry, Minister of State for Energy* [154]

She went on to state the importance of wave and tidal stream demonstrating potential to compete with other sources of low carbon generation:

> *"while Britain has some of the best tidal stream resources in the world, the potential to develop projects must be viewed in the context of the Government's Clean Growth Strategy, Industrial Strategy and the falling costs of other forms of low carbon generation, such as offshore wind." – Claire Perry, Minister of State for Energy* [154]

In essence, Perry restated the "triple test" that she discussed at the launch of the Government's Clean Growth Strategy in 2017 [43], where she explained that support for emerging tidal stream and wave technologies:

> *"So we have a new triple test to help us decide how to support new technologies:*
> *First, does this deliver maximum carbon emission reduction?*
> *Second, can we see a clear cost reduction pathway for this technology, so we can deliver low cost solutions?*
> *And third, can the UK develop world-leading technology in a sizeable global market?" – Claire Perry, Minister of State for Energy* [43]

5.5.1.2 Government motives

In setting policy, Government is responding to a number of motives. First of all, as a member of the global community, the UK must take account of international pressures – both formal and informal:

> *"From G7 and from the UN down there's such a lobby and such a force of Government and I suppose media" - SC20*

"Almost everybody says that there are very good reasons to support climate change and drive down emissions. But the reality is unless your statutory framework supports that, people don't do it." – PM65

"So you've got the recognition that we need to decarbonise and in some quarters it's recognised that you pretty much need to pull every lever you've got going. That's obviously got to balance with the giving value for money." – SO75

So the whole dynamic has really gone through a paradigm shift really, of where we were five years ago and where we are now. So it's those big economic and political factors which have really driven it." – WTG12

"The climate change agenda put renewables on the map and focussed minds about how we're going to decarbonise our energy system, and the electricity system as a subset of that." – SH40

"The Labour government said it wanted to do more on renewables…climate change politics was just starting." - SO34

5.5.1.3 Government actions

In the context of international pressure, the UK Government was seen as wanting to develop and maintain a nationally competitive stance:

"Certainly in this country we were - government-wise and policy-wise - well behind the curve when it came to offshore wind. I think compared to your Danes and your Swedes, Portuguese, Spanish, I think that."- PM55

"In the UK there was a perception that we were late, we had to catch up." – SO34

Government therefore developed policy to enable the transition and to make a statement about what it wanted to happen in the UK:

"I'd put the Climate Change Act and the CO_2 targets that the UK government and the EU have set themselves." – WPD5

"When the government came in it said there's going to be capacity, when the Crown Estate came in and said there's going to be leasing rounds - then you saw the utilities come in." – SO74

"We needed a beacon out there, to which we could sail" – WPD7

Features of policy described by interviewees were wide-ranging, and included arrangements for deployment through leasing, the implementation of support systems, regulatory arrangements:

> *"Setting the frameworks for the [Offshore wind leasing] round 1, the round 2, the round 3, SEAs [Strategic Environmental Assessments], the role of the Crown Estate, setting the economic and financial parameters – ROCS and transition though Electricity Market Reform to Contracts for Difference – all of those are absolutely critical and driven by the UK overarching policy on climate change and to meet our climate change obligations." – SH43*

> *"So we've had some really good support systems, through the renewables obligation previously and now the CFD scheme that has dictated, at an energy policy level, the direction of travel." - WTG12*

> *"Well obviously it's the economics tools, through tax incentives, it can offer support in terms of research grants, it can drive research working with the universities and the further educational institutes, it can support small companies get off the ground and get into the sector through all these various fields, it can offer support." – PM55*

> *"I think the government probably did the right thing putting all the grid under one operator." – SC14*

5.5.1.4 The importance of policy

Interviewees widely recognised the importance of policy, and cited examples in the UK and elsewhere as being important in driving the energy transition. Policy was seen to be important both practically, by helping to develop or define business models, but also culturally, by legitimising this field of activity:

> *"And regulated policy builds the business models for those to take place. And that plays out at a number of levels. It plays out at a high level in terms of the business model around whether it's ROCs, whether it's CFDs, whether it's carbon trading. But it also plays out at a lower level as well, in terms of Internet of Things, web services and these kinds of things." – SO74*

> *"So look at the activity in Canada: what has mobilized the people, the activity, the global interest in going into the Bay of Fundy[6] - it's having that feed-in tariff, and having the political will to want to go and do this, because ultimately that will remove the barriers - the regulatory, the onshore*

---

[6] The Bay of Fundy lies in Canada between Nova Scotia and Newfoundland, and has the highest tidal range in the world, making it an attractive site for tidal stream energy development

elements - it removes those barriers or lessens them and makes them smoother for the technology to come in behind this." – MPD72

"Supplying a supportive environment is important." – SO75

"I think the onus is on the government to produce a policy which drives the market." – MTD22

5.5.1.5 Constraints on policy - the energy trilemma

Government has to negotiate between at least three factors – often characterised as the "energy trilemma" – adequate power-generating capacity, meeting emissions reductions targets and keeping cost acceptable for consumer. This was clearly expressed by WTG12:

"So for a long time we've talked about this three way triangle that government faces an issue that lots of our existing electricity generating plant - be it coal or nuclear is coming off the system, so we need lots of new generation. The second leg of that is the need to decarbonise - the whole climate change, fossil fuel, renewables targets stuff led us a long way down that path. And the third was the need to minimise cost to consumers." – WTG12

Other interviewees also mentioned the energy trilemma as a constraining factor for Government:

"We understand that UK government was (pre 2016) under pressure from UK public to get cost of energy down.' – SH36

"It's really the cost and value of ensuring that we are getting the energy mix at the right sort of value to the consumer and to government." – SH43

Interviewees noted that government was alert to the benefits of supporting the sector, in terms of jobs created and Gross Value Added:

"I think the government's potentially been driven by the promise of jobs and economic wealth, GVA. Credit where it's due, you know, I honestly would never have thought I'd be sitting in the UK, we'd be the global leader in offshore wind." – SC56

The tidal stream sector in particular is now using this argument to justify further support:

"If you look at what happened in Scotland, with EMEC, it drove a huge amount of private investment from all over the world. I don't know how many developers they've had there now - quite a few. But you know, it's 19 different countries and £23.4 million into the Orcadian economy on the basis of "we will put some money in, we will provide you with access and a site and we'll allow you to go ahead and chuck your kit in the water". MPD72

5.5.1.6 Government competence

Interviewees were generally of the view that, within the context of the energy trilemma, government was largely committed to the climate change agenda, but some noted that its delivery did not always match its aspirations:

"There's a difference between political will and political competence." – SH43

"I think the government's been missing in action in terms of setting the mid term [goals]." – SC56

"I think we could have got twice as far with half the money, in half the time, if we had had clear strategic direction and that the funding would follow that." – MTD58

"Often the high level aspiration is excellent but the detail of fulfilment is weak. Interestingly, take the Scottish energy and environment policy - we want the whole system view, we want it to be fair to people, we want smart systems and we want greener systems." – WPD63

5.5.1.7 Policy stability

Many interviewees raised the issue of policy stability. It was seen as critical, as WPD1 stated clearly:

"Without the right government signals and the right government policies it wouldn't have happened. And that's not just around the government of the day, it's also around political consensus. What's enabled the UK to thrive is the fact that successive governments have managed to get strong cross party signals together about offshore wind and I think that that is very important for investors, particularly if you're an investor based overseas." – WPD1

Others agreed that policy stability was desirable:

"What they all say is they need - what they need most is continuity…and I think certain changes in government policy have made things more stop/go." – SO37

However, a number of interviewees cited examples of policy instability, arising through a recognition of the costs of existing policy support or through tensions between government departments:

> *"A hugely declining interest as the administration at the UK level changed, for any further support for these very expensive technologies as they were viewed at the time." – SO34*

> *"And if the government keeps intervening, with regulation or legislation, to skew a maturity horizon that they themselves had laid out in the first place, particularly when a lot of money has being spent already - and they've done that time and time again, then investors will lose confidence in the growth strategies and development targets." – WPD63*

> *"However government funding regimes and therefore sources of development capital changed radically overnight during our path to commercialisation." – MPD24*

One specific example was the impact of Electricity Market Reform – a change to the structure of the electricity market implemented in 2012 which altered how offshore wind, tidal stream and wave energy developments should be supported:

> *"The impact of EMR was to park the whole industry for about five years." – WTG15*

5.5.1.8 Impact of business on policy

While interviewees recognised the importance of policy on business; they also recognised that dialogue with government was desirable in trying to ensure that policy was workable for business.

> *"There is little point in developing a business that is at variance with government policy because it's very very difficult as we have found out on many occasions to lobby and change policy. It is possible but it's very hard…It's extremely important to keep abreast of what the policy is today, what those changes look like and also how we can try to affect that change." – SC10*

The formation of industry bodies was seen to be able to assist in managing dialogue with government:

> *"BWEA was formed to try to have a more structured conversation with government." – SO34*

Some implied or expressed concerns that lobbying was not equally available to all participants, and that its effects were not necessarily transparent:

> *"I think there must have been some dialogue between government and the developers." – SO37*
>
> *"Lobbying and funds and party donations…goes on every single day." – MPD24*

5.5.1.9 Too big, too soon

Some interviewees noted that policy may drive sub-optimal outcomes, described in the industry as "too big, too soon". MacGillivray [71] has explored this issue, and the interviewees in this research noted that it was important that policy did not drive industry to attempt technology delivery which was not feasible.

> *"I think that part of the reason that it hasn't developed as well as I would have liked to see it develop is because of that government policy, where that where most of the people who've been involved in it and indeed most of the developers have looked at going large straightaway - developing big devices and putting them in in big arrays and basically displacing power stations." – MTD22*
>
> *"There's just this big drive - we must get grid connected wave devices at any cost. 100% funding and all these kind of things." – MTD64*
>
> *"Because the wave and tidal developers had made those promises to the private sector, they then used the same set of policies to agree a policy framework to deliver wave and tidal. And so you have a set of goalposts that were far too ambitious And so in terms of policy support - it was actually a great policy support mechanism for a while, but they just weren't ready for it. So industry was fixated on utility scale machines, because they sold the venture capital industry the fact they were going to be providing super cheap energy and this is going to be a revolution." – SH40*

5.5.1.10 Subnational factors

UK government is not the only policy-setting entity with a bearing on offshore wind, tidal stream and wave energy in the UK. European Union directives can provide a framework within which national policies are developed, and the Scottish government and the Welsh government can also implement policies affecting these sectors.

It was noted that the motivations of these subnational governments were not necessarily aligned with the UK government:

> *"I think the Scottish Government is a government which has a nationalist agenda and so if it's good for Scotland it's gets a tick, and if it's not good for Scotland it doesn't get a tick. So they look at it in a regional sense, you might say, or a parochial sense, which isn't good." – MTD22*

5.5.2 Actors, institutions and networks

5.5.2.1 Actors

While Government is clearly seen as the most important actor in terms of Guidance of the Search, all other actors in the sector have roles to play in evolving and implementing policies.

Actor	Typical activities	Wind vs Tidal Stream and Wave
UK Government	Policy design and implementation, financial support (tax, R&D funding, subsidies), R&D direction and funding, regulatory development and implementation, supportive culture	Similar responsibilities, but different policies appropriate for different sectors
Super-national entities (e.g. EU, UN, UNFCCC)	Setting over-arching direction (e.g. European Climate Change Directive, Paris Agreement)	Not differentiated
Subnational government	Operating within limitations of power determined by UK Government, can be supportive	Scottish government historically very supportive of marine sector (now also floating wind), Welsh government also very pro-tidal/wave
Technology and project developers	Dialogue with government to influence and shape policy	Wind has much more coherent and impactful voice, due to scale and organisation. Marine sector trying to organise to improve effectiveness
Supply chain	Some scope to participate in dialogue with government, especially infrastructure (e.g. National Grid)	No differentiation
Support organisations	Facilitate implementation of government policy (e.g.	Some sector wide (e.g. Carbon Trust), some

	directing funding, dialogue on policy setting), provide frameworks for industry collaboration	focussed on marine (e.g. EMEC) or wave only (Wave Energy Scotland)

Table 5-7: F4 - actors and activities (author's analysis)

5.5.2.2 Institutions

Guidance of the search relies on hard and soft institutions.

"Hard Institutions"

A range of "hard" institutions have been critical to guidance of the search. The most important is the UK Government, but super-national bodies (such as the UN Framework Convention on Climate Change and the European Union directorates in Climate Action, Energy and Environment) are also important in influencing how the UK sets policy. Even national governments outside the UK can indirectly influence policy in the UK, as the UK government is aware of its competitive positioning:

> *"I think it's mostly been driven by government policy, and in particular European government policy and then latterly American government policy although there's been some drive to develop tidal in Korea and China as well." – MTD22*

Subnational governments (Scottish government, Welsh government) are also important in guiding policy, although their policy-making scope is governed by the decisions on which powers are reserved to UK government, and which are devolved. To give an example, in 2006 the Scottish government had the power to define support policies for marine renewables, and it exercised this power by defining and implementing the Marine Supply Obligation – an incentive programme structured similarly to the Renewables Obligation but explicitly targeted on tidal stream and wave power [155]. This system was later incorporated into the "banded" Renewables Obligation, whose cancellation was announced in 2013 [156] and implemented in 2017. The cancellation of the RO and the introduction of the CfD involved the reversion of policy in relation to renewable energy support to Westminster.

Subnational governments can still "guide the search", for example through mechanisms such as the Saltire Prize[7] [157].

"Soft institutions"

The guidance of the search relies on a culture in which Government and other policy-setting entities can successfully engage with the actors in industry who will implement these policies.

This relies on a degree of trust between developers and investors on the one side, and government (or the agencies providing financial and other support) on the other side. Over many years, this trust has been developed by government acting responsibly and "grandfathering" support structures so that investors receive the returns for which they had invested. For example, when the Government consulted on the replacement of the Renewables Obligation [156], it ensured that projects in the development pipeline on which significant investment had already been made would still receive support under the RO (which is what they had expected when the investment decision was made).

5.5.2.3 Networks

The networks in F4 Guidance of the Search comprise the Government, as policy setter, and actors in the sector, as those responding to the policy. As noted in Section 5.5.1.8, the benefit of dialogue between the party setting policy and those carrying it out, and expecting to make a commercial return, allows for policy to be tuned in response to lessons gained during its implementation.

This network extends to support institutions, whether government-funded (Carbon Trust, Scottish Enterprise) or industry-funded (e.g. RenewableUK,

---

[7] The Saltire Prize [157] was created by the Scottish government to "accelerate the commercial development of wave and tidal energy technology". It was originally to award £10 million to the first developer to export not less than 100 GWh to the electricity grid from the power of the sea. It was reconfigured in early 2019 to be a fund to "help commercial deployment of tidal projects".

formerly British Wind Energy Association). The value of these institutions was described by MTD64:

"We've had a lot of support from Scottish Enterprise and government bodies to get it through development." – MTD64

At root, the motivation for government to engage with the TIS, at least once it demonstrated capacity to contribute to UK generation in a significant way, was the desire to maintain continuity of supply. As WPD1 explained:

"I think political expediency was 'we've got to make sure we continue to invest in generation infrastructure or all the lights may go out' which is the death knell for any politician." – WPD1

Part of government's strategy was to explicitly encourage the development of a sector network, and a supply chain engaged with this:

"What I do see is a trend for more collaboration which is driven partly by government…it's extremely important to keep abreast of what the policy is today, what those changes look like and also how we can try to affect that change." – SC10

Government encouraged the development of sector networks, by making it clear what was required of the industry as a whole [158]:

"In 2012, we had something called the Cost Reduction Task Force that a lot of the major players participated in, which was all about meeting the government's challenge because at the time there was a promise that government would continue to support offshore wind as long as costs continued to fall." – WTG12

5.5.3 Metrics, indicators and drivers

Metric / Indicator / Driver	Offshore wind	Comments	Marine	Comments
Targets set by governments / funding bodies	Yes	Offshore Wind Sector Deal has formalised targets [47]	No	No explicit targets for roll-out defined in policy
Numbers of articles in	Yes	Increasing numbers of offshore wind-	Limited	Articles in general renewables

professional journals		focussed publications		journals, limited dedicated journals
Policy action plans	Yes	Offshore Wind Sector Deal has strengthened policy in this sector [47]	No	Marine sector seeking policy engagement with UK government
Quality of academic and industry discussion	Good	Active industry discussion but only somewhat active academic discussion	Very active academic discussion of wave, limited tidal	Very limited industry discussion known
Mapping specific government or industry targets	Good	Offshore Wind Sector Deal defines targets	Limited	ORE Catapult cost reduction report [150] indicates possible roll out
Policy support and effectiveness	Strong	Large	Poor	Marine fails "triple test" so struggling for support

Table 5-8: F4 metrics, indicators and drivers: offshore wind and marine (author's analysis)

5.5.4 Validity

The sheer volume of comments from interviewees on F4 – Guidance of the Search strongly support its validity as a function in TIS. The average score in the analysis was 4.42, with a low standard deviation of 1.02. This average score was the highest for any of the seven Hekkert functions, further supporting its validity.

This quantitative assessment was supported by the qualitative comments in support of the function:

> *"It's been fundamental for offshore wind." – WTG12*
>
> *"You need that [F4 Guidance of the Search] to make things happen." – SC14*
>
> *"I think without it in reality you don't get anywhere." – MTD22*
>
> *"I'd be tempted to say [the] government role is important." – PM29*
>
> *"Policy is quite critical to create an industry like offshore wind." – SO32*

"It wasn't a bottom-up process, so government was important." – SO34

"We see it is extremely important and is essential in the development of new technologies and bringing them to market." – SH36

"Nothing would happen without government guidance in this industry. Having the level of political will to effect this transition is absolutely critical." – SH43

"It's really important in wave and tidal. You've got to set up a clear vision about how investment in the sector can make a return." – MTD58

"I think in the end the starting point was government policy." – WPD7

"Really, really important. And the reason they're really important is they drive investor confidence." – MPD72

"It's hugely – there is probably nothing more important. And without the government policy, the UK wouldn't have the largest installed base on offshore wind; without the right government policy it would have no offshore wind." – SO74

"It's absolutely essential." – SO77

The lowest score received was 1, from a tidal technology developer which had explicitly adopted a strategy which insulated it from policy questions. As it stated, the intrinsic volatility in the political environment was seen to be unmanageable, so the company had deliberately defined an approach in which policy choices (and specifically financial support schemes) were not relied upon:

"Democracy changes every five years, that's asking for the impossible." – MTD64

It is therefore not surprising that this interviewee attributed little importance to this function, but the unique strategy adopted by this interviewee's organisation is not considered to compromise the importance of this function as part of the TIS.

5.5.4.1 Sectoral analysis

Figure 5-12 shows the average scores for F4 – Guidance of the search by respondent group. Scores were almost universally high, with exceptions in Marine Technology Developers and Policy Makers.

Marine Technology Developers currently appear to be frustrated by what they may perceive to be a lack of policy direction and this may be reflected in this low score. This may well be a misperception, however, as the Energy Minister's clearly expressed "triple test" [43], which requires new energy technologies to deliver maximum carbon emission reduction, to show a clear cost reduction pathway for this technology, so we can deliver low cost solutions and to offer the UK potential develop world-leading technology in a sizeable global market, is currently not met by this sector. In the context of this test, it can be argued that Government is right to leave marine technologies entirely to the private sector.

It is curious that Policy Makers score F4 - Guidance of the Search at a lower level than most other respondents, as one might have expected them to attribute more value to the area in which they are most directly engaged. PM29 seemed to acknowledge the important role of policy:

> *"What I've heard from industry and financiers on the guidance of the search - a consistent signal from government is important." – PM29*

PM49 felt that policy should be stronger and suggested an ambivalence towards a supportive policy on the part of government. This might partially explain the low weighting attributed to it:

> *"I think this policy should be stronger to ensure more local content/local engagement." - PM49*
>
> *"But the political steer for the policy has aided it to a degree; it could have been so much more successful if you had government that was very keen - but then they're wanting to get cheap electricity for the voters." – PM49*

This ambivalence was put in terms of the broader commercial context by PM55:

> *"But it shouldn't be doing so at the expense of other sectors which might be more commercially viable because at the end of the day, it's taxpayers' money we've got to remember." – PM55*

It seems that the low score attributed to F4 Guidance of the Search by Policy Makers might be attributable to their better knowledge of the effectiveness and commitment to policy from government, potentially making its weaknesses clearer to them than to other observers.

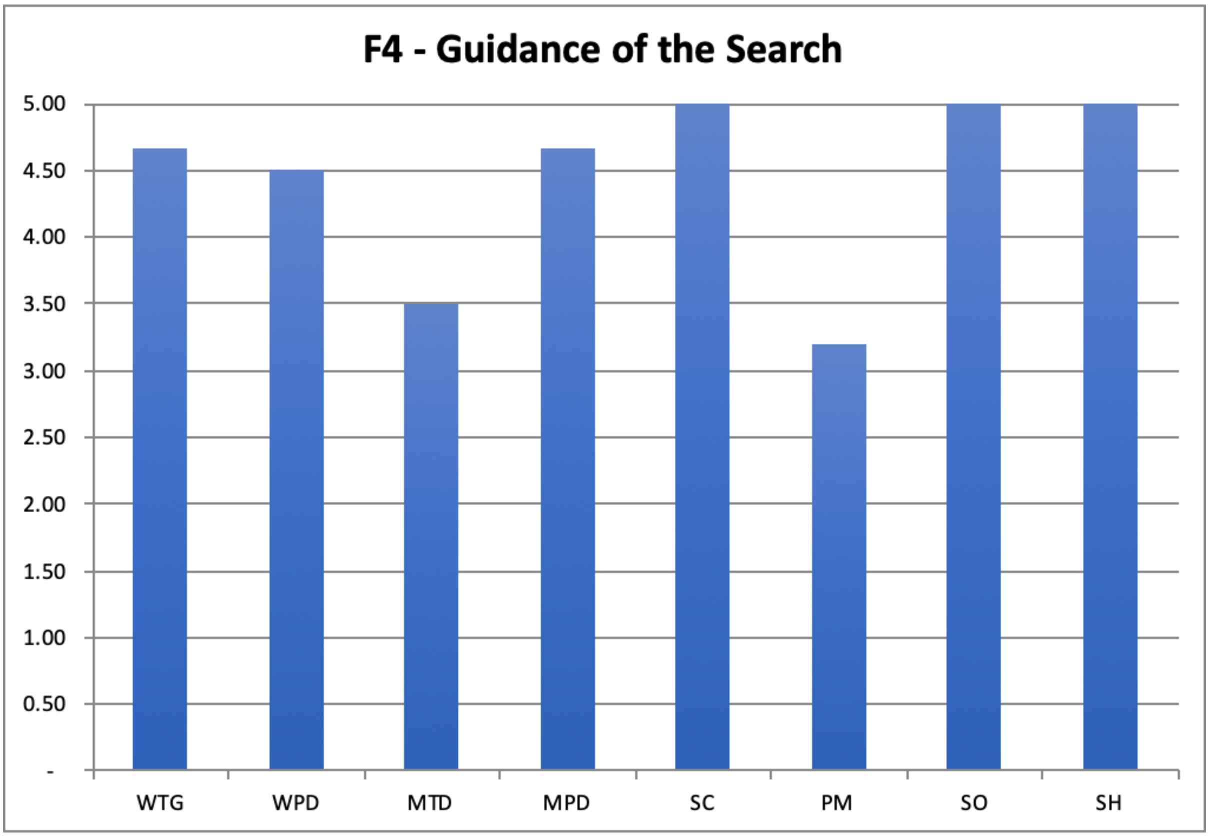

Figure 5-12: Analysis of F4 – Guidance of the Search by respondent group (author's analysis) ; Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

5.5.5 Conclusion - F4 – Guidance of the Search

The importance of Guidance of the Search, which interviewees interpreted as policy setting, definition and implementation of regulatory and leasing terms, was very widely agreed to be critical to the evolution of the TIS.

In some definitions, Guidance of the Search might be considered to include financial support arrangements (grants, revenue support, tax credits etc.), but these have been included in this analysis as part of F5 Market Formation.

5.6 F5 - Market Formation

> *"Without the support of governments we wouldn't have had the change, and then once you get to a certain point then it becomes a self-fulfilling prophecy." – WPD7*

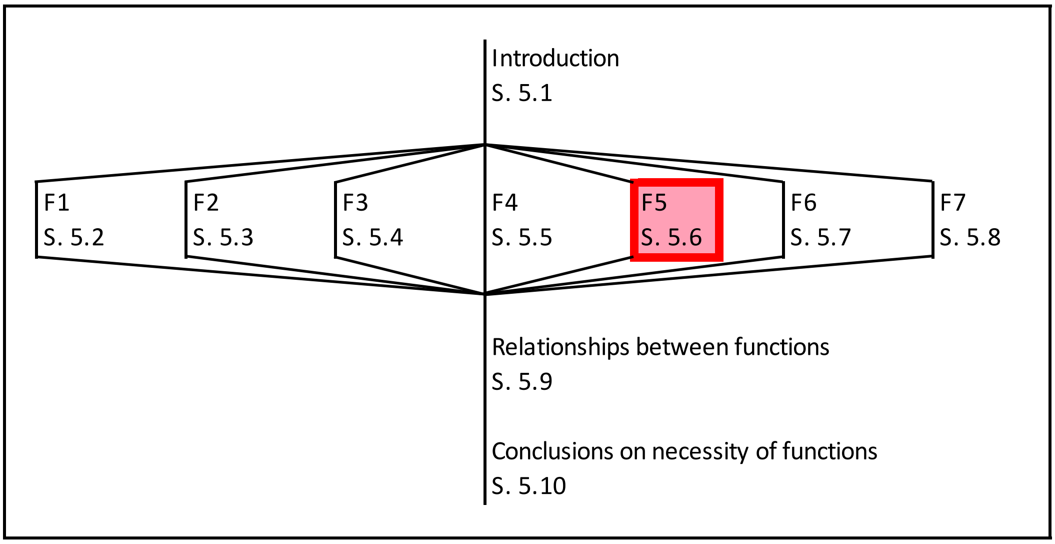

Figure 5-13: Section 5.6 roadmap

5.6.1 Key themes

Interviewees widely agreed that that market formation was a necessary step in the development of the TIS. However, there was a strong focus in the interviews on the creation of incentives and their effect and effectiveness in encouraging the development of cost-competitive technologies.

The themes relating to incentives included their structuring and perceived generosity, the importance of continuity in incentives and the paradoxical need for them to evolve at the same time.

Other key themes which emerged considered the wider role of government and communities in enabling market development, the importance of confidence in a future market, the roles of developers in building this market, the importance of developing a healthy supply chain and the road map to subsidy-free operation. Finally, the challenge of forming a market for marine technologies, especially in the context of the relative advancement of the offshore wind sector, was a strong theme among the marine-sector interviewees.

5.6.1.1 Incentives

Interviewees widely took the view that the creation of appropriate incentives was critical in market formation. As WPD1 said:

> *"Without the ROC banding it wouldn't have happened." – WPD1*

The interviewees explored the design for these incentives and recognised that design of appropriate incentive structures is not easy:

> *"So there are elements of this system being unfair but it's awfully easy to criticise the system and awfully difficult to come up with a fair one." – MTD22*

Structure and generosity

There was considerable agreement that the structure of incentive systems, specifically the introduction of the Renewables Obligation, the transition through FID Enabling to the competitive Contracts for Difference had been appropriate to the needs of the offshore wind sector.

> *"There's one major reason why offshore wind is so competitive now. Beyond the wildest dreams of anyone five years ago - is competition and the CFD process. You have to take your hat off to the government. In that regard, it's not perfect, but they got it right. Because it was instrumental in driving cost down. And it's instrumental in developing the 12 megawatt, the 15 megawatt, future turbines." – SC10*

> *"We've had the technology NFFO route where you tried to encourage new technologies but we have no market for them to go to. We then had the ROC system which seemed to work, but then with was perceived to be too expensive and then wasn't a level playing field with other technologies, because it was too biased towards renewables. The impact of EMR was to park the whole industry for about five years. The positive consequence of that is that arguably the auction regime, when it did come through, drove down costs or at least price, and drove up competition and that's been a positive outcome." – WTG15*

> *"The RO was a brilliant thing because if you had a grid connection and a consent you were in. So that built a great deal of stability and there were a few bells and whistles along the way in how the RO worked, but that was basically how everyone understood it to work. And I think that was very good. It was a very generous thing. The CFD has also been similarly good. The only point I make about the CFD is that it would be better had the government committed early on to annual auctions. I think that would have really built in the idea of visibility of a pipeline." – PM30*

However, it was recognised that the fast-moving nature of the cost base for offshore wind meant that the incentive system could be overly generous in some circumstances, although that generosity achieved other benefits:

> *"The transition to CFD has maintained momentum, through some deliberate acts. The early CFDs, which were heavily criticized as being too generous, of course maintained the momentum and allowed more supply chain investment and kept things going." – WTG12*

Continuity and evolution

Interviewees referred to the paradoxical need for incentives to be long-lived, to allow for certainty on investment returns, and yet to react to changes in the cost base of the emergent technology:

> *"How consistent has it been? Not very - it's been consistent in its slow steady incremental approach." – SO74*

> *"So the development of the subsidy scheme and the clear signal that it's not going to be around forever and the competition between the developers are really the main cost drivers." – WPD5*

> *"I think within the 2020s in the UK, we'll move to more of a power purchase agreement, no subsidies." – SC56*

It is apparent that interviewees considered that the structure of incentives in the offshore wind sector has been very effective at driving cost down and creating a roadmap to subsidy-free operation.

5.6.1.2 The role of government

The role of the government was seen to be critical in market formation, but interviewees believed it extended beyond simply designing and implementing incentives. Unsurprisingly, a clear policy framework was seen to be important:

> *"Of course a clear policy framework to invest is key." – SO60*

The government tool kit was seen to extend well beyond incentives:

> *"Well obviously it's the economics tools, through tax incentives, it can offer support in terms of research grants, it can drive research working with the universities and the further educational institutes, it can support small*

> *companies get off the ground and get into the sector through all these various fields, it can offer support." – PM55*

While Government was seen to have a range of tools, continuing interference in policy or its delivery was seen to be a negative factor for investors:

> *"If the government keeps intervening, with regulation or legislation, to skew a maturity horizon that they themselves had laid out in the first place, particularly when a lot of money has been spent already – they've done that time and time again, then investors will lose confidence in the growth strategies and development targets." - WPD63*

Government's motives, which were explored in Section 5.5.1.1, were further explained:

> *"I think the government's potentially been driven by the promise of jobs and economic wealth, GVA." – SC56*

Government was also recognised to have a role in creating the right culture for collaboration and innovation:

> *"That's where the public sector can come in and create that environment to create collaboration. And to a certain extent, it has happened." – MPD59*

Finally, a number of interviewees noted that as costs for offshore wind reached parity with generation alternatives, the importance of the government role naturally declined:

> *"I think there'll be pressure on us to continue to reduce costs and of course once you get below wholesale price, then the government's leverage diminishes to a degree." – WTG12*

> *"Once the role of government is about supporting that initial R&D and that innovation space, helping companies potentially through that valley of death point of funding. But then once the technology is cost effective you don't need that." – PM29*

5.6.1.3 The role of communities

The formation of a market was seen to involve many other participants in addition to government. The role of communities was explicitly noted by WPD63:

"The role of communities in energy provision and ownership I think is something that will grow, but to mature and drive emerging technologies is going to need a stronger connection between up and coming research for its own right and a final application in the field." – WPD63

"There's an increasing appetite based on the need for a long term sustainable future." – SH43

On a smaller scale, Orkney was described as a microcosm for market formation, in the marine sector:

"You see it in a micro environment in Orkney with the European Marine Energy Centre where effectively the Orkney community has turned to renewables and it's actually boosted the economy." – SO77

This community support for the formation of a market is clearly strongly linked to the perceived legitimacy of the technology, and this is explored further in Section 5.8, which considers F7 – Legitimation.

5.6.1.4 Confidence in the future market

Formation of the market requires confidence in the future market, as investors will not be prepared to make an investment without some reassurance that they will generate the anticipated returns. Some interviewees described the macro environment in power generation, in which coal-fired power generation is being decommissioned, and the nuclear industry faces challenges:

"There's a lot of coal fired power stations coming to the end of life, a lot of nuclear power plant coming to the end of its life. And a lot of people saying well actually these things need replaced because the overall demand for electricity hasn't gone down, in fact demand is going to go up. If we move more to electric cars, whatever we could be changing all the trains in Scotland go from diesel to electric - electrical local demand is going up. Even if we get more efficient. But supply is disappearing, because the old plants are disappearing. So you have to replace it with something - the market fundamentals are there - we need new generation." – SC14

Others cited the increasing depth of the market giving confidence in the requirement for new generating capacity:

"But the issue there is the physical depth of the market place and that's about installed generating capacity - and the more there is, in theory, the deeper the market will get and the more competition there will be, just because there's more CFDs available." – SC20

"We've actually got a market. There are things to bid for." – SO37

The developing visibility of the development pipeline contributes strongly to this perception of market confidence:

"It's recently, and that the last two or three months been bolder - in that now with the announcement of CFDs for the next 10 years - actually I think will have a huge impact. I think it suddenly gives a runway to companies which they never thought they had." – SO74

5.6.1.5 The role of developers

The interviewees recognised that there was a societal shift towards a low carbon transition under way, and that some companies embedded in the carbon-based energy economy, such as utilities and oil and gas companies, recognised an existential threat over the medium term:

"But in the end they see that the end of the hydrocarbon era is coming and these companies have to find something that will extend their life past it." – WPD7

When the circumstances were right, these companies felt emboldened to act:

"When they government came in and said 'there's going to be capacity', when the Crown Estate came in and said 'there's going to be leasing rounds' - then you saw the utilities come in." – SO74

This led, in some interviewees' views, to a virtuous circle driven by competition between developers, which could accelerate the development of the market:

"So I'm not surprised some of the established IOCs[8] get back into this, because they realize: since the Paris climate change agreement, the signup of the climate change initiative, where they're part of a recognition that it

[8] International Oil Companies, including Shell, Equinor (formerly Statoil), Ørsted (formerly DONG) and others

is actually as the world we're going to be in, we'd better lead, not being followers, is probably the right space to be in." – SO60

"So, thinking about offshore wind for a moment. I think what happened there was the market size got interesting. People realized well actually we could make some money out of this. So you started seeing utility companies get serious about project development." – SO60

"It's only really in the past, in the relatively recent past, that this has become principally a utility-driven development." – WPD5

5.6.1.6 A healthy supply chain

Interviewees believed that market formation needed more than the positive engagement of the government and developers, but also that a healthy supply chain was important:

"I think that the key, crux move there was DONG Energy (as it was at the time) placing an order for several hundred Siemens 3MW machines. And they bought turbines they didn't have projects for yet. But the placement of that order meant that they drove down costs incredibly." – SH40

"You can see how developers are making sure they give orders to both [main Wind Turbine manufacturers] to keep competition in the market. And the FIDER contracts that came through, which were expensive compared to the CFD auction prices that we subsequently had, they essentially allowed a set of companies to contract with Siemens particularly and bring the blade factory to Hull, and it wouldn't have happened without those." – SO34

It was recognised that without the formation of a robust market and a strong pipeline, these wider economic benefits (jobs, investment, GVA) would be lost:

"Companies would find it hard to stay and expand in the UK without a pipeline of projects." – SH36

Integrating these views, interviewees were describing a clear roadmap to subsidy-free deployment, through the timely and well-structured deployment of incentives, with communities, operators and the supply responding to these signals with investment and resource mobilisation (see Section 5.7). A number of interviewees recognised that incentives could not be limitless, and that Government had to take account of the broad benefits potentially offered by a technology in considering appropriate incentives (see also F4, Section 5.5). This limit was highlighted by one policy maker, for which it loomed large:

"But it shouldn't be doing so at the expense of other sectors which might be more commercially viable because at the end of the day, it's taxpayers' money we've got to remember." – PM55

5.6.1.7 Marine incentives

Interviewees involved in the marine space found a number of differences between the treatment of offshore wind, and tidal stream and wave.

"Offshore wind had different support mechanisms at early stages of deployment and there was a more consistent evolution of support at the different stages, whereas [for] wave and tidal there is not considered to be an accessible subsidy support and so some developers are looking at options as to whether they can continue running their companies at risk. Momentum is changing in the tidal sector in particular and therefore these companies are working hard to encourage a positive decision on future support." – SH36

Participant SO37 suggested that the marine and tidal sectors recognise that they are not cost competitive with offshore wind, and their response has been to ask for special treatment:

"I think that the response to that from me and from the industry is 'no, we've got to try and persuade them to put the incentives in'. They've done it for virtually every other new industry, why shouldn't they do it for wave and tidal, just because it's further away?" – SO37

A number of interviewees identified an issue with the tidal stream and wave sectors "over-promising" on their cost and development trajectory, in order to secure private sector funding, with this leading to government setting unachievable performance targets for incentives:

"With wave and tidal, I think what's happened is the industry have had to be fairly bullish to secure their investments from...certainly from the private sector, they've had to promise a lot. And generally they under delivered on those promises, because actually it was a pretty tough gig. And I think most people who were raising money for VC realized they were over-promising at the time but, you know, that's the nature of the beast for private money…Because the wave and tidal developers had made those promises to the private sector, they then used the same set of policies to agree a policy framework to deliver wave and tidal. And so you have a set of goalposts that were far too ambitious…And so in terms of policy support -

it was actually a great policy support mechanism for a while, but they just weren't ready for it." – SH40

An interviewee from a support organisation felt that government had moved the goal posts for marine technology development:

"At the same time, generating subsidy is very important to any new technology. And I think in the same way that the government sort of pulled the rug on solar maybe too early, it's definitely done that for wave and tidal." – SO77

This was supported by another interviewee, who felt that the vicious circle of limited R&D spend leading to a limited development pipeline and so on, was limiting the sector:

"I think that's also where wave and tidal are struggling because you don't have a pipeline and therefore it makes it very difficult to justify a large R&D spend." – SO32

One marine developer called for a "market prize" as an incentive for innovation:

"And what I continue to argue vociferously for - if there's one thing you can do - put a market prize back up. It's what's delivered every single technical innovation - not necessarily conventional electricity generation market - it's for solar, it's off-grid, the ability to do things you wouldn't be able to do if you didn't have it. It is a route to market and it drives private investment." – MTD58

5.6.2 Actors, institutions and networks

5.6.2.1 Actors

Actor	Typical activities	Wind vs Tidal Stream and Wave
Government	Determines funding support design, implements incentives	Government has defined "technology-blind" support system in CfD, making marine uncompetitive.
Funding agencies	Implement funding and grant support schemes	CfD mechanism technology-blind; limited scope for targeting funding support on marine

Technology developers	Dialogue with government, investment in product development, manufacture	WTG manufacturers investing in manufacturing capacity in UK; marine developers in dialogue over incentives
Project developers	Dialogue with government, investment in projects	Wind project developers now able to attract third party capital funding, on basis of CfD; marine developers struggling to attract funding
Supply chain	Engagement with market opportunity, investment in facilities	Active wind supply chain; limited marine supply chain as technologies largely prototypes
Support organisations	Engagement with technology and project developers, government	Seek to maximise communication between industry and government
Communities	Engagement with development of market sector	Mostly addressed under F7 – Legitimation (see Section 5.8)

Table 5-9: F5 - actors and activities (author's analysis)

5.6.2.2 Institutions

Market formation relies heavily on the hard institutions around incentives, but soft institutions also have a role to play.

"Hard Institutions"

The hard institutions at work in market formation include the arrangements for incentive allocation, as determined by government from time to time, as well as the formal leasing and licensing arrangements under which project developers can access resources.

The importance of incentives in market formation is clear from the interview review. The evolution from NFFO, through RO and FIDER to CFD and the development of incentives in co-evolution with the development of the technologies and projects is discussed in Section [9.2.1].

"Soft institutions"

Market formation relies on a number of soft institutions, including the culture of trust between government and recipient of incentives and the tradition that government will not retrospectively change incentive mechanisms.

The definition of explicit targets for deployment, such as the targets for 30 GW of offshore wind deployment by 2030 in the Sector Deal and the creation of 27,000 jobs [47] might be considered a hard or soft institution in the context of F5 Market Formation, but whether hard or soft, it unambiguously contributes to the function.

5.6.2.3 Networks

Market formation is driven by a complex interplay between government and its agencies, who design and implement incentive schemes, regulate and provide access to resources through leasing, technology suppliers and project developers.

Formal networks are largely the same as those identified in Section 5.5.2.3 for F4 – Guidance of the Search, and comprise industry-led groups including RenewableUK, Scottish Renewables, and government-sponsored bodies such as Offshore Wind Cost Reduction Task Force, EMEC and others. These networks assist with market formation by enabling dialogue between the technology and the government, informing policy making and incentive development.

Informal networks develop around projects and around centres of manufacturing capacity. Projects develop networks involving project developers, supply chain participants and local communities, while manufacturing centres develop networks involving their own subsidiary supply chains and local communities. These informal networks allow the market to take root in relevant localities, building legitimacy (see Section 5.8) and encouraging additional investment.

5.6.3 Metrics, indicators and drivers

Metric / Indicator / Driver	Offshore wind	Comments	Marine	Comments
Numbers of niche markets	Few	Offshore wind focussed on grid scale deployment	Some	Some marine developers focussing on specialist niches (oil & gas; islands)
Specific tax regimes	None	No special tax treatment	None	No special tax treatment
New environmental and other standards	None	No special standards, permitting now clear	None	No special standards, permitting now clear
Supportive regulatory regime	Good	Mature market with clear pipeline	Acceptable	Regulatory regime supportive of prototype testing
Development of standards	Good	Mature market	Poor	Technologies still essentially prototypes
Public market support	Good	Strong support for all renewables in BEIS surveys	Good	Strong support for all renewables in BEIS surveys
Incentives and subsidies	Good	CfD now well established, with clear pipeline	Poor	Marine effectively unable to compete for CfD, few other funding routes
Willingness of retail customers to pay premium for "green"	Good	Robust business models demonstrated by Ecotricity, Bulb etc	Good	Robust business models demonstrated by Ecotricity, Bulb etc

Table 5-10: F5 metrics, indicators and drivers: offshore wind and marine (author's analysis)

5.6.4 Validity

Interviewees strongly supported market formation as a necessary function in emergence of the TIS. The average score for market formation was 4.00 with a standard deviation of 1.24.

This quantitative assessment was supported by the comments from interviewees:

> *"Without the ROC banding it wouldn't have happened." – WPD1*
>
> *"But the fact is that grants – they work well." – WTG78*
>
> *"The RO was a brilliant thing…the CFD has also been similarly good." – PM30*
>
> *"The CfD has been hugely successful in creating competition to decrease the costs of offshore wind." – SH36*
>
> *"So very important. And it has to be proportional and responsive to what it's trying to deliver." – MPD72*
>
> *"It's vitally important…The ROC scheme seemed to work well for those initial projects, it got the ball rolling." – SH43*
>
> *"Without the support of governments we wouldn't have had the change." – WPD7*

The lowest score received on market formation was from WPD5, who scored it 1. This is puzzling, as WPD5 described the importance of incentives in the development of new technologies and their markets:

> *"I will caveat that by saying that the enhanced ROC scheme for demonstration projects such as Hywind, EOWDC, Kincardine - that's very much necessary because a small scale project is simply not commercially viable without an enhanced subsidy scheme, and I think it is very important that we are able to test and demonstrate new technologies on a limited scale." – WPD5*

This is a strong endorsement of the importance of market formation, including incentives, in TIS evolution and the function's validity is not felt to be challenged by this individual low score.

5.6.4.1 Sectoral analysis

Figure 5-14 shows the average scores for F5 - Market Formation by respondent group. Market formation scored highest among Wind Turbine Generator manufacturers (WTG) and lowest among Wind Project Developers (WPD). WTG income is driven by the development of the market, in which they therefore have a keen interest, while Wind Project Developers are thought to take the view that the market is developing well and little further stimulus (in the form of creation of "protected spaces" is required.

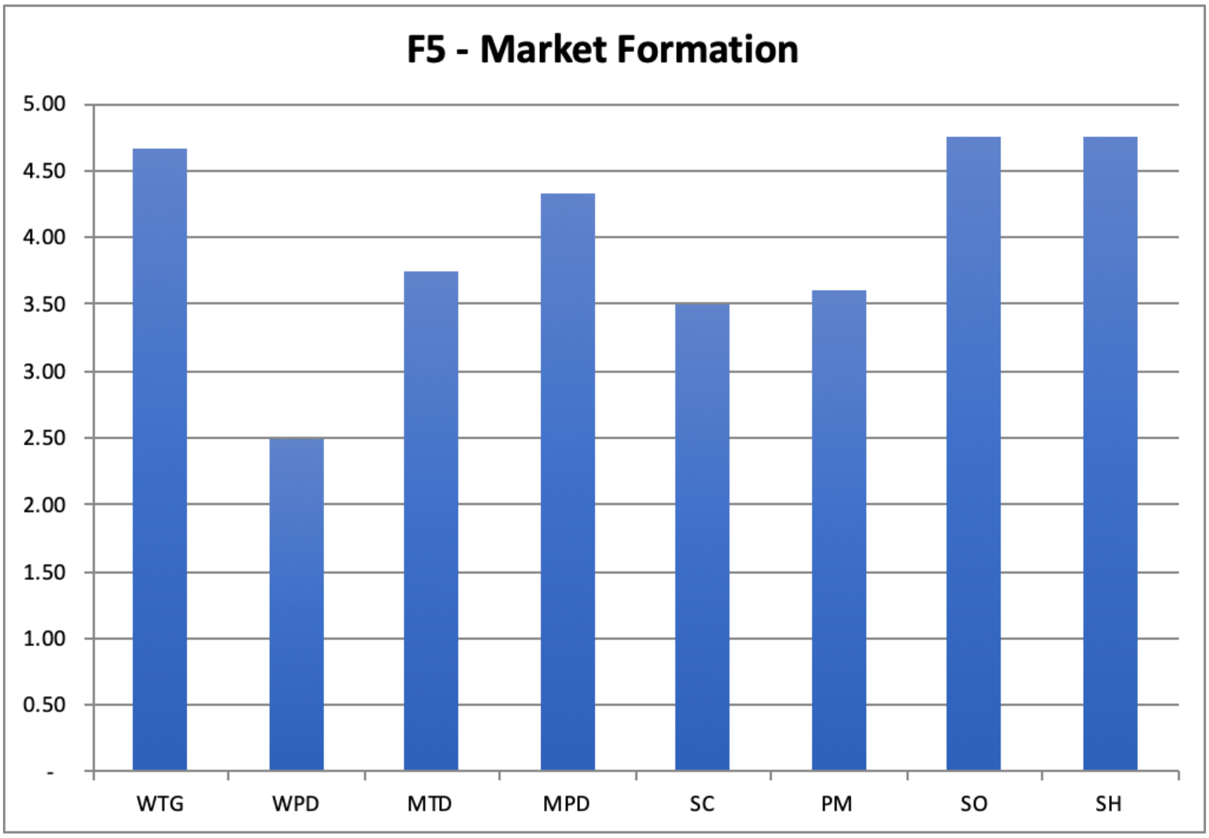

Figure 5-14: Analysis of F5 - Market formation by respondent group (author's analysis) ; Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

5.6.5 Conclusion – F5 – Market Formation

Market formation, including the implementation of incentives, was widely agreed by the research participants to be critical to the evolution of a TIS.

Market formation, as described by the interviewees, included the development and implementation by government of a policy framework, including the design and roll-out of incentive schemes, regulatory arrangements and leasing and licensing of access to resources. The industry's contribution to market formation involves investment in technologies and projects in response to this governmental encouragement (which clearly overlaps with F4 Guidance of the Search), and relationship building with the supply chain and affected communities to secure support for implementation of the technology.

It is clear that offshore wind has progressed further towards market formation than either tidal stream and wave, and that this is largely due to the significant cost reductions offshore wind has achieved.

5.7 F6 - Resource Mobilisation

"Why do companies take decisions? If they see a future in it." – PM55

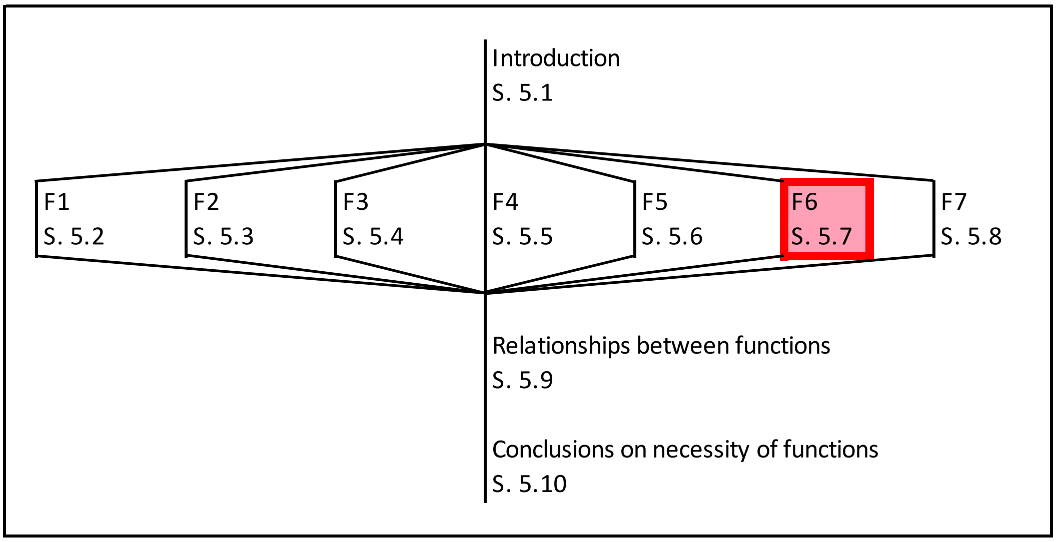

Figure 5-15: Section 5.7 roadmap

5.7.1 Key themes

Resource mobilisation was generally acknowledged as a vital element in the emergence of the TIS, although there was a strong suggestion that the mobilisation of resources into a clear market opportunity was "business as usual" and often took place later in the life of a TIS. The temporal relationships between the functions, of which this is an example, are discussed further in Section 5.9.2).

Key themes which emerged were

- the mobilisation of resources in response to a perceived market opportunity
- other motivations for mobilising resources
- the alignment of resource mobilisation to general business strategy
- the roles of diversification and consolidation
- changes in investability and sources of capital
- differences between resource mobilisation in offshore wind and marine and
- the links between mobilisation of resources and the commercial potential for the technology.

5.7.1.1 Mobilisation of resources in response to market opportunity

Many interviewees either said or suggested that the key factor in driving mobilisation of resources was the visibility of the market opportunity and the potential to generate a return on investment.

> *"I think it's to do with the economic opportunity if you think about the long term." - PM29*

> *"In terms of a return, in terms of a regular opportunity to bid in, in terms of the amount of capacity that would be procured, in terms of the price that they would receive for that power." - PM30*

> *"So for the globals to really take an interest, it's got to be seen as a likely candidate for core business or something where they can make some money." – SO77*

> *"So, thinking about offshore wind for a moment. I think what happened there was the market size got interesting. People realized: 'well actually we could make some money out of this'. So you started seeing utility companies get serious about project development." - SH40*

> *"I think it's clear line of sight on a route to market. It's that long term horizon - that this can scale up, that it can be more than just innovation and that there is a market." – MPD72*

This criterion for mobilisation of resources was relevant to project developers and supply chain alike, as the supply chain was seen to have responded to access the opportunity once the developer led the way:

> *"I think the main point is that offshore wind didn't require much innovation but it did require the supply chain to step up... which they did." MTD58*

> *"I mean if you've got a funded project with a live tender for equipment or services, the supply chain responds to it." – MPD24*

In response to the question of what do you think it would take to get resource mobilisation to happen, SO77 replied clearly:

> *"It's got to be a clear understanding of the market opportunity and a return on investment." – SO77*

5.7.1.2 Other motivations for mobilisation

The mobilisation of resource, particularly before the market was strongly established, was seen by the participants to be motivated by other factors. These factors included disaffection with the oil and gas industry, and the desire to do something more positive for society:

> *"Where a lot of people come into offshore wind has been people who are disenfranchised with oil and gas, or fed up with the commute and actually want to do something a bit more...get to a certain age and want to do something a bit more sustainable with their life." – SC14*
>
> *"Oil and gas is not seen as an exciting industry anymore, and they're seeing young graduates having no desire to go into it even though the wages are great." – PM30*
>
> *"So the thing is you can sit in a room and say "aren't we all doing a great thing". You hear that consistently at any conference you go to." – PM30*
>
> *"I think that the earliest stage, mobilisation of resources probably is driven a bit more by passion and personal interest and desire to see outcomes." – SH40*

These motivations were seen to drive both individuals and corporates, but for the latter, they were described in terms of diversification using existing skill sets. This is explored in Section 6.7.1.3.

5.7.1.3 Business strategy and "business as usual"

Resource mobilisation within the TIS takes place through the implementation of business strategies. The business context influences the overall business strategy and can force resource allocation:

> *"I don't think that we can really expect to be in the business unless we are prepared to allocate resources in terms of financial, people and facility. And we are now doing that and putting our money where our mouth is." – SC10*

As assets mature, they require renewal, and this too can drive resource mobilisation into the emerging TIS, especially as its maturity develops and its perceived risk declines:

> *"I think a lot of utilities have lot of ageing assets and they're looking at replacement anyway and they're probably becoming less efficient, more*

difficult, less efficient than new technology. And I think probably quite a lot thinking that they have to decommission these why replace them with the same thing. Let's replace them with something that's 50 to 100 years more modern." - SO37

Finally, although interviewees focused on the first of Keynes' "animal spirits" of hope and fear [159] in citing factors driving strategic choices, fear was also seen to be a driver:

> *"The other element is around it's growing so much faster than the oil and gas market – can you afford not to be in it?" – SO60*

5.7.1.4 Diversification and consolidation

Diversification, by applying existing skills to new business sectors, and consolidation, by acquiring complementary businesses, are both entirely conventional business strategies [160]. Both of these strategies were cited and are used:

> *"We look at that in two ways. One way is to grow organically, and the other way is through an M&A proposition." – SC10*

> *"It's changed of course. Scale has meant that there's been a lot of market consolidation. When I started looking at offshore wind, there were about 20 different turbine manufacturers saying they were going to the UK and sell turbines into the Round 3 projects; we effectively we have two now." – WTG12*

Diversification can mean redeploying an existing work force or moving resources from outside the UK to within it (or vice versa), and can assist with managing business risk:

> *"So you have to spread your risk, diversify more and new energy is a route to diversify your business." – PM49*

> *"That's another interesting shift: the oil and gas industry moving into utilities" – SO37*

> *"On the utility side - you've got a lot of people who in the past might have been designing a nuclear power station or a coal fired power station or a gas station have just been moved across into working on renewables." – SC14*

> *"All of the development community are either oil gas majors or utility scale generators. They're not all obviously retail in the UK but most of them are retail somewhere in the world or very large scale IPPs. They are international businesses…they have a portfolio of development and construction and operating assets. They recycle capital between them and they move stuff around between different countries depending on the fortunes of the projects in those countries." – WTG15*

The supply chain has also diversified into the offshore wind sector, as it recognises the scale of the opportunity:

> *"We've seen these massive behemoth infrastructure companies, funded through institutional investors, become another version of vertically integrated utilities. You know, they are doing everything in-house and extracting all the margins they can and offshoring as much of the manufacturing as possible." – PM30*
>
> *"Existing businesses can expand or diversify their businesses where they identify market opportunities." – SH36*

The parallels between oil and gas and offshore wind (and tidal stream and wave) projects and operations, and the resulting opportunities for the oil and gas supply chain, were noted by a number of interviewees:

> *"In Scotland we've got an historic oil and gas sector which holds offshore knowhow and there is therefore crossover with other newer offshore technologies. However it is important to look for the specifics of where that crossover exists, and create opportunities which are attractive to offshore-based workers." – SH36*
>
> *"Once we started to get serious offshore contractors involved then we started to see properly engineered foundation solutions." – SH40*

5.7.1.5 Changes in investability

The de-risking of offshore wind through progressive implementation and refinements to revenue support mechanisms, specifically the change from the RO to CfD, led to an increase in its potential for investment. This in turn led to greater availability of capital and a virtuous circle between increased deployment and decreased investment risk.

> *"If you look at the offshore wind, it's also interesting that pension funds are now funding some of it. So you've got that long term investment infrastructure play." – PM29*

"So the Green Investment Bank was set up to help provide money. But it was always a bit of an odd institution (a) it wasn't a bank, and (b) it was only allowed to lend on commercial terms. So it basically used its association with government to pump prime and bring in other investors, so it played a sort of – it didn't do what it said it did, but it brought in money and reassured other investors that this was a good project or a good way to invest money." – SO34

"So if you now look at who the investors in offshore wind are, you've got pension funds as well as the utilities, you've got big capital – Siemens' capital arm, other companies have capital arms - DEME Group[9] for example– they've got a capital arm, and they like to invest in wind farms as a way of levering the contracts to deliver projects." - SO34

"I think we've touched upon the game changing issue, you've now got kind of pension fund money - you know - I think the finance side of it is absolutely turned on its head." – SC56

"Offshore wind is absolutely bankable." – SC56

5.7.1.6 Differences between offshore wind and marine

Resource mobilisation in the marine sector is less advanced than in offshore wind, as fewer large projects have been developed. The relatively greater risk in the marine sector, and the history of government funding, was seen to have limited the availability of private funding:

"One challenge that is of course that it's now a long way back to getting private investment to come back in, having created 100% public funding. It makes it harder for funding to come back in." - MTD58

Early promises of commercial performance by wave and tidal developers attracted private investors, leading to later problems. As PM30 put it:

"Some of the investors in those wave technologies were entirely the wrong investors; they were looking for quick payback which you don't get in a hardcore development for a technology like that." PM30

PM65 explained that policy makers continue to try to attract private funding:

"We wanted to go through a process in wave and start to bring the private sector in, so they could see that this this technology had somewhere to go, that we were doing it properly and bring their money with them to the table

[9] DEME Group is a large Belgian shipping group)

and then obviously the balance of investment would change as we got towards commercialization." – PM65

Although the marine sector was seen to have challenges in attracting financial resources, the sector continues to make its case in terms of other benefits that it could bring, should resources be mobilised in its favour:

"And that's meant that, because of the good resource we've got in the UK, because of that that policy investment, because of strong academic interest, we've been the magnet where people have come to develop wave and tidal technology." – SO77

"And it's probably the export opportunity and it's certainly the export opportunity for wave that's attractive, but then there's the other dimension which is of interest to parts of government and that geographic importance and the importance of place. And we see that ports and port infrastructure is very important, and wave and tidal deployment sees an influx of capital support into ports that otherwise would need support from other areas, so our fishing industry is in decline, our shipbuilding is in decline - but things like wave and tidal actually reverse that." – SO77

5.7.2 Actors, institutions and networks

5.7.2.1 Actors

The actors identified in earlier sections are also critical participants in the delivery of F6 – Resource Mobilisation. Table 5-11 summarises the key roles of these actors.

Actor	Typical activities	Wind vs Tidal Stream and Wave
Government	Setting targets, providing financial support mechanisms	Government now focussed on offshore wind as scale option; limited support for resource mobilisation in marine
Technology developers	De-risking technology through progressive deployment and innovation	WTG manufacturers highly consolidated and well financed, marine developers much smaller and less well resourced
Project developers	Delivering capacity, driving costs down	Project delivery in offshore wind well established; marine projects only in tidal and are bespoke
Supply chain	Delivering capacity, driving costs down, innovating services	Supply chain active in offshore wind sector with active competition; marine sector providing many fewer, much smaller opportunities
Financiers	Allocating investment capital	Offshore wind risk profile widely acceptable to range of investors; marine projects still hard to finance

Table 5-11: F6 - actors and activities (author's analysis)

5.7.2.2 Institutions

"Hard Institutions"

The hard institutions driving resource mobilisation are largely the mechanisms that give participants confidence of their financial return. These include the financial support mechanisms, comprising the RO and CfD as well as other grant support such as the EU Horizon 2020 programme, together with the confidence in the rule of law governing such transactions.

"Soft institutions"

Less formally, soft institutions at work in resource mobilisation include the general attitudes to risk and confidence in the technology in the minds of potential investors. In this case, a fear of overexposure to risk by being an early investor has evolved into a fear of missing out, as the industry perception of the security of returns offered by offshore wind projects has become much more acceptable.

Once again, Watts [146] adds to the discussion on institutions, describing the failure of Pelamis as due to a critical mismatch:

> *"The speed of technology not matching the financial investment expectation."* - [146]*, p346*

Watts' point is that the financial support system must co-evolve with the technology, to maintain the prospect of an acceptable return at all points during the evolution of the technology.

5.7.2.3 Networks

The networks driving resource mobilisation are also similar to those driving the earlier functions. The industry associations (RenewablesUK, ORE Catapult, EWEA) and project development joint ventures are networks which enable resource mobilisation by securing support for, and delivering projects.

Informal networks also exist among the finance community and through the extensive (and increasing) roster of conferences, at which participants in the sector meet to discuss and validate their decisions and strategies.

In one case, MTD64 complained that these networks could limit innovative thinking, as a "groupthink" or conventional wisdom could make it hard for a new participant to make its investment case:

> *"Because investors, just as much as the general public, often can just group you as soon as they see you - before you get a chance to open your mouth, it's 'oh, we've seen this before'." – MTD64*

The networks are not always supportive of the function, although in general the success of offshore wind points to the networks within that sector being constructive.

5.7.3 Metrics, indicators and drivers

Metric / Indicator / Driver	Offshore wind	Comments	Marine	Comments
Funds made available for R&D	Limited from government; high from industry	R&D now funded by profitable industry	Very limited from both government and industry	Marine still in prototyping stage, but funds limited
Funds for testing	Limited from government; high from industry	Testing now funded by profitable industry	Very limited from both government and industry	Marine still in prototyping stage, but funds limited
Numbers of workers in sector	Many	Strong resource mobilisation under way in both developers and supply chain in response to build-out of capacity and Sector Deal [47]	Few	Multiple technology developers, but each has few employees
Development of innovative financing	Strong	Increasingly funding coming from pension funds, insurance companies as risk profile declines	Emerging	Industry seeking innovative financing solutions with government

ICT access	Good	Well financed and innovative developers deploying value-adding ICT solutions	Poor	Poorly financed developers focussed on technical performance
Venture capital deals	No longer required	Funding has moved to lower risk, lower return profile (balance sheet debt, project finance)	Rarely required	Earlier VC investment (e.g.. Pelamis, Aquamarine) failed, VC network now very cautious
Cooperation across supply chain	Good	Well designed and managed projects coordinate supply chain	Poor	Mostly small technology developers accessing supply chain on ad-hoc basis

Table 5-12: F6 metrics, indicators and drivers: offshore wind and marine (author's analysis)

5.7.4 Validity

The interviewees strongly supported the validity of F6 – Resource Mobilisation in the emerging TIS. The offshore wind sector clearly recognises that this function is well advanced, while the marine sector, and especially the marine technology developers, felt that this function was not strongly expressed in that sector.

The average score for F6 was 3.38, with a standard error of the mean of 1.08, strongly confirming its place as a function in the evolution of the TIS.

Subjective comments in support of resource mobilisation as a necessary function in the emergence of the TIS included:

> *"Because obviously as we're growing the renewables business, there is an increase in the headcount, the internal resource count at our end and our supplies has to increase. So there is a very large degree of resource mobilization in the renewables business at this moment." – WPD5*
>
> *"Offshore wind didn't require much innovation but it did require the supply chain step up…which they did." – MTD58*
>
> *"[The importance of resource mobilisation is] very high, I'd say." – MPD59*

"The supply chain gets it." – SO60

The lowest score for F6 (of 1) was given by a marine technology developer who felt that resource mobilisation:

"hasn't started yet" – MTD22

This interviewee was not challenging the requirement for resource mobilisation as part of the emergence of the TIS; rather, they were bemoaning that it had yet to begin in the marine sector. They felt, however, that resource mobilisation just required a technological breakthrough:

> *"I think that the day that any renewable energy developer comes out with a technology where they say we can actually produce this technology and we can produce the energy from this technology cheaper then we can produce it from gas or oil...the major energy companies, such as Statoil in particular is a good example at the moment, BP and all the others...are going to be all over that market." – MTD22*

5.7.4.1 Sectoral analysis

Figure 5-16 shows the average scores for F6 – Resource Mobilisation by respondent group.

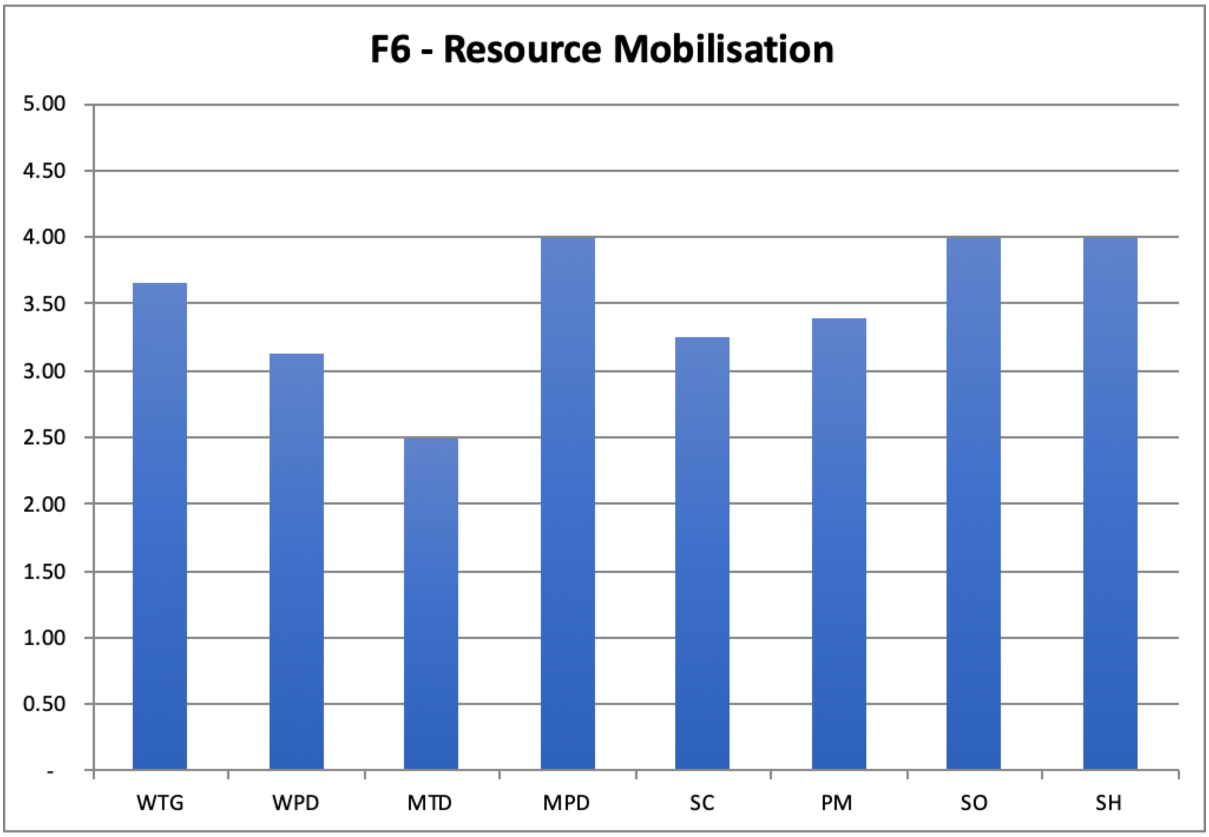

Figure 5-16: Analysis of F6 – Resource mobilisation by respondent group (author's analysis) ; Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

All respondent groups scored 2.5 or more, supporting the validity of the function. The lowest scoring respondent group was the marine technology developers (MTD), whose views have been discussed above, while all other groups rated the function above the median value of 2.5.

5.7.5 Conclusion – F6 – Resource Mobilisation

In conclusion, there was strong support across the respondent groups for Resource Mobilisation as a necessary function in the emergent TIS. F6 - Resource Mobilisation was seen to include the deployment of personnel, equipment and capital, and the interaction between the revenue support mechanism (RO or CfD), the maturity of the technology and the degree of deployment was seen to be critical in creating a virtuous funding/deployment circle. This is explored further in Section 5.9.

5.8 F7 - Legitimation

> *"I think certainly the acceptance of offshore wind at a time when onshore wind became a real hot potato in political terms, offshore wind certainly became more favoured because it's 'not in my backyard', further from shore." – SH43*

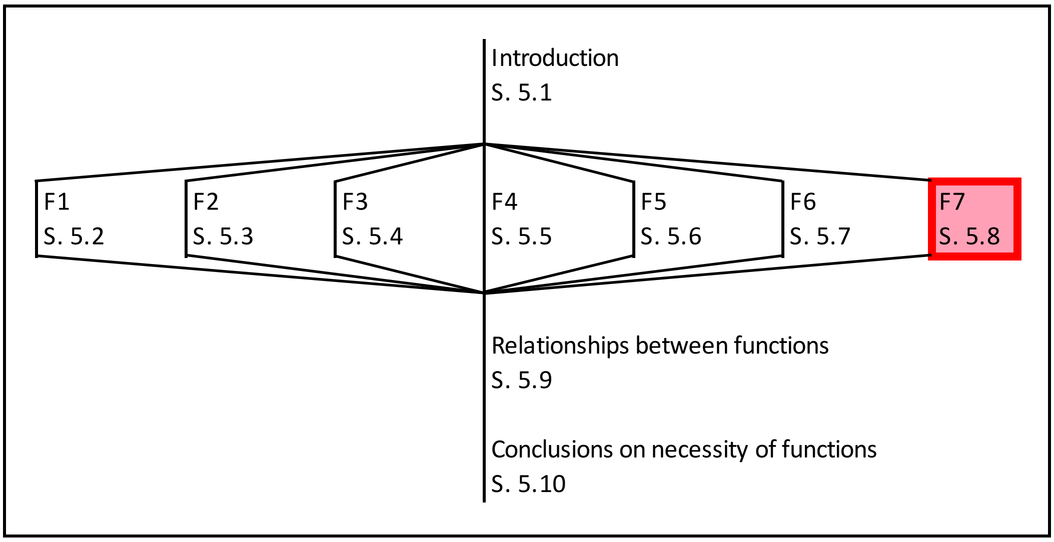

Figure 5-17: Section 5.8 roadmap

5.8.1 Key themes

Legitimation and what one interviewee described as the "social licence to operate" were widely seen to be a factor in the evolution of the TIS.

Key themes which emerged included

- the general level of support and the effect of general social attitudes to climate change
- the "energy trilemma" and the additional benefits offered by the TIS
- the role of the industry in building its own legitimacy and the effect on legitimation of successful delivery
- the interplay between onshore and offshore wind and question of responsibility
- the differences in legitimacy between offshore wind and marine.
-

5.8.1.1 General support and social attitudes

A number of interviewees pointed to a high level of support in society for renewables in general, and offshore wind and marine in particular:

"I think when we come to public acceptance and those kind of things, and obviously that's incredibly high for offshore wind, so I think the argument has been won." WTG12

"If you look at the current ratings, the vast majority of the British public support onshore wind. It gets more complicated when it is local to them. And has visual impact on them. And then it has more of a Marmite effect - people love it or hate it…but actually the socialization is, I would say, widely adopted. You don't see the resistance now. You don't see the nonsense articles or the letters to the Times." WTG15

"The societal view of offshore wind is inherently favourable." – PM55

"I think that tidal power has a very strong social license to operate. If you look at the number of followers that our company has in social media or whatever else." MPD24

"There's public support for wave and tidal." SH36

As a side-note, it was noted that public interest does not necessarily equate to public action:

"They may well have all signed a petition or something, but when it comes to turning up to a public inquiry to complain, they were not actually that motivated." SC14

MPD24 agreed with this, noting that:

"tidal power has a very strong social licence to operate." – MPD24

However, MPD24 highlighted that societal support did not necessarily translate into successful project developments:

"Once again, it can prevent a project going ahead on a micro scale, but on a macro scale I don't think it matters that much. I know that people adore what we did. We had 7000 letters written into the relevant minister, and it didn't make any difference." – MPD24

There was a widely held view that changing social attitudes towards climate change were influential in building societal support for the energy transition:

"Yes but there is something more going on as well, which I think is the acceptance of the green agenda." SO37

"But I think also that society has changed." PM49

"I think that overwhelmingly people now are of the opinion that we need to reduce our carbon emissions in this country." – PM55

"Society is still changing. I don't think people necessarily understand the full implications of the energy transition, because it's a very complicated issue." – MPD59

5.8.1.2 The energy trilemma and additional benefits

The energy trilemma – the balance between low cost energy, low emissions energy and security of supply [43] – was seen by some participants as limiting the legitimacy of offshore wind and marine. They explained that the challenge for renewables was to find a legitimate place in the energy mix in the context of the trilemma. Obviously, one of the strengths of renewables would be the low emissions leg of the trilemma:

"The idea that renewables was the big first bold step that the UK could make into its national contribution to climate change and that we were going to grab this new industry and make it a UK one." PM30

"There's an increasing appetite based on the need for a long term sustainable energy future." SH43

"So in conjunction with the closing down of coal production and the burning of real black dirty stuff, I think the socialization is very high." WTG15

"For most of us who work in renewables, it's important that renewables is moving in the right direction, developing innovation and increasing diversity of supply in the efforts to tackle climate change." – SH36

Offshore wind and marine also sought to build legitimacy by pointing to other benefits arising from the deployment of these technologies:

"So some are doing really well at promoting the benefits, whether it be for environmental reasons, economic reasons etc." – PM49

There was seen to be a focus on Gross Value Added and employment opportunities:

"I think in offshore wind terms in Scotland, the other thing that was promised was jobs." PM30

"I think that offshore wind ticks the same box. And it's also helped by the fact that offshore wind has come to some very economically challenged

areas that traditionally governments have supported - I'm talking about Barrow in Furness, Heysham and areas like that - Hull, Grimsby." – MTD58

However, it was recognised that this argument had not always been effective:

"Almost none of those offshore wind jobs arrived, certainly not in the time they were due to arrive". – PM30

There were also perceived challenges to the legitimacy of offshore wind:

"There's still a perception amongst the public that we're still paying extra for offshore wind farms - we're paying a green levy." – SC56

"The only anti argument at the moment really is the cost of electricity. There are definitely people making politics out of saying 'well the cost is going up because of all this investment in renewables, and we shouldn't be investing in renewables, we should be pulling the cost of electricity down and UK electricity is more expensive than the rest of Europe' and all kind of stuff. And a lot of that is misinformation. But it resonates with if somebody's got a big electricity bill coming through the door." – SC14.

There were also specific challenges, as in the case of Mainstream's Neart na Gaoithe project, although this showed that it was possible to shift the legitimacy dialogue from a narrow agenda (in its case, impact on bird life) to a wider frame (including the creation of local jobs and locally added value), as SC10 made clear:

"I think that offshore wind took a big leap forward during that painful exercise[10] *for Mainstream (as they were at the time) because they put together a coalition of a supply chain to actually try to get the public to understand, through the media, that this windfarm is legitimate - it has to be built because of the positive effect on our communities and jobs. And so what happened in the end was that employment and investment and GVA in communities became more important and they won the battle against the preservation of birdlife offshore." - SC10*

5.8.1.3 Building legitimacy – the role of the industry and the effect of delivery

[10] Mainstream Renewable Power's Neart na Gaoithe offshore wind project was involved in a lengthy legal dispute with the Royal Society for the Protection of Birds which delayed development consent for a number of years.

A number of interviewees pointed to the importance of a track record of delivery in building the case for the legitimacy of the sector. In particular, offshore wind was considered to have strengthened its case by achieving delivery of capacity and cost reduction targets ahead of expectations:

> *"Offshore wind has worked pretty well. And I think offshore wind has managed to get successes in the right order, as they pledged to government; government has seen more progress than they expected…They've over delivered on that promise and that's given Government a huge amount of confidence." – SH40*

> *"I think over the last seven to eight years we've seen more projects built, more projects actually in the water turning and burning and a lot of social concerns about some of those projects have faded to a certain degree. So the more activity that is seen by the general public in the sector through resource mobilization, the more legitimation that it gets." – SH43*

> *"When you go to an area where there's been more than one round of wind farms, you see a very different picture. For example, the last project I worked on was in the Thames Estuary. It was an extension to a previous wind farm. And I must say there was actually no opposition - no opposition to the project and encouragement by local politicians many of whom abhor renewable energy on principle, on grounds of principle. The council was very supportive, residents who see the impact that the industry has in terms of generating business and generating jobs." - WPD5*

Participant SC56 suggested that this legitimacy has contributed to the Sector Deal:

> *"I think the industry has proved itself. I think it's come together with some really good prospecting developers - the likes of Ørsted, the likes of RWE, and the government to its credit has now said 'if you deliver the targets we set…', which the industry has, they're now coming to the table and we're talking about a Sector Deal, which if it all comes together would be 30 gigawatts by 2030 which is an incredible industry rise over the next 12 years." – SC56*

The role of the press in influencing public opinion and building legitimacy was highlighted by participant SH43:

> *"But I think overall the press coverage in the last few years has gradually become more favourable towards offshore wind." – SH43*

The track record of the marine sector has been less positive and this is addressed in Section 5.8.1.5).

5.8.1.4 Interplay of onshore wind and offshore wind

The interplay in legitimacy between onshore and offshore wind is complex, with onshore wind contributing to the legitimacy of offshore wind both by example and by difference.

Firstly, the demonstration of wind technology through the deployment of onshore wind has leant legitimacy to offshore wind, especially in the latter's early years:

> *"But I think it (onshore wind) has played a big part in making it (wind power in general) the norm." PM49*

However, the growth in numbers of objectors to onshore wind as its deployment increased has challenged the legitimacy of onshore wind:

> *"There's still a huge lobby of hill walkers and bird enthusiasts who don't like onshore wind." SC20*

Some participants suggested that the existence of offshore wind has allowed objectors to onshore wind to shift their support for the societally-legitimated deployment of renewables to offshore wind:

> *"There is a growing NIMBY attitude towards wind onshore and therefore - wind onshore is still one of the cheapest sources of electricity generation or has become over the last few years - but there's a saturation where people won't accept it anymore…I think the NIMBY thing has driven wind offshore." SC14*

> *"I think - the challenges that we see with onshore wind, in terms of its acceptance, are benefiting offshore wind." SO32*

> *"I think certainly the acceptance of offshore wind at a time when onshore wind became a real hot potato in political terms offshore wind certainly became more favoured because it's 'not in my backyard' – it's further away from shore." – SH43*

5.8.1.5 Differences between offshore wind and marine

Wave and tidal stream technologies appear to appeal to the national myth of a seafaring nation in a way that offshore wind does not. As a number of interviewees pointed out, this encourages government and public support for these technologies:

> *"This is what Greg Barker 'Secretary of State for Energy] always used to say - he said the blue rinse brigade - they all love marine energy. They say 'Britannia rules the waves'. They see that the great maritime nation, that made it quite easy for them, from a voter perception perspective, to be very supportive, and probably remains the case today." – MTD58*
>
> *"I think most people want to see wave energy succeed." – SH40*
>
> *"So I think that there is a very strong social acceptance that wave and tidal is a good thing." – SO77*

Participants revealed that the legitimacy of marine renewables is challenged by a number of factors. One is a failure in the popular view to recognise that the development of new technologies always carries with it a risk of failure:

> *"The point is that nobody understands, everybody's forgotten the wind turbines that fell over, everybody's forgotten the solar panels that opaque after a week in the sun. Everybody's forgotten about the rockets that crashed... because they're now mature and accepted technology. This is all just part and parcel of a new technology coming forward." MTD58*

Another was the potential confusion between wave, tidal stream and tidal range:

> *"So I think we do have a real societal issue about raising awareness of exactly what tidal energy and wave energy is. I think people still get confused and don't understand the difference between tidal range, barrages, lagoons and tidal stream and they sort of lump it all into one. And I fear that even our UK government does the same thing - in fact I know they do." – SO77*

Other factors that have had a negative impact on the legitimacy of the sector that were highlighted by participants included excessive hype and over-stated expectations, high-profile failures, including Pelamis and Aquamarine, and withdrawals by investors and failures to get projects approved, such as the proposed Swansea Bay tidal lagoon:

"Reflecting on the history of wave development and the demise of Aquamarine - I think there was probably too much hype in the sector." MPD59

"We saw Siemens getting involved a few years ago through Marine Current Turbines, maybe even others. I think, as an observer, I would say, it felt like 'okay this is a great move. This is this is what the sector needs'. Because I think the ability to develop and deploy the technology under your own steam, because you can see that route to making a profit ultimately, is important. So when they subsequently withdrew, and we had similar stories with Rolls-Royce, it had looked like the right people were getting involved and then when they withdrew that really felt like are a big wake up call, and a big warning that actually the people who should understand the technology and the conditions and how to make money out of, it didn't fancy it much." – SO75

"I think it's very topical for a different reason, this week probably, with the lagoon again in particular, which had full buy-in from the population, full buy-in from all the reports that were done saying that it looked like a good idea. And it's now not going to go ahead." MTD22

"The legitimacy of the tidal power industry has taken a credibility blow through the arduous process that Tidal Lagoon Power took us on, through their proposed Swansea Bay Tidal Lagoon Project." MTD24

5.8.2 Actors, institutions and networks

5.8.2.1 Actors

Actor	Typical activities	Wind vs Tidal Stream and Wave
Government and policy makers	Influence legitimacy though policy setting and public statements	Sector Deal strongly legitimises offshore wind; marine not being legitimised at present by government
Technology and project developers, supply chain	Build legitimacy through project delivery, constructive engagement with stakeholders and public	Higher levels of activity in wind strengthen its legitimacy relative to marine; marine developers striving to make their case
Support organisations	Support deployment and assist with making the case for the of technologies	Support organisations working to support both sectors
Media and opinion formers	Influence public opinion	Emphasis on offshore wind over marine (see Section 5.4.3.1)

Table 5-13: F7 - actors and activities (author's analysis)

Although the general public play a key role in the legitimation of offshore wind and marine renewables, they are not considered to be an actor as their participation is essentially reactive, and in response to changes in the landscape, regime and niches (in Geels' terms) which arise either through actions of the actors or exogenously-generated changes to the landscape.

The general public can be considered to be a critical network in relation to legitimation for offshore renewables, and this is explored in Section 5.8.2.3.

5.8.2.2 Institutions

"Hard Institutions"

Legitimation does not rely heavily on hard institutions, as it is characterised by opinion and feeling, rather than constrained by rules or regulations. As has been seen in many functions, the boundary between networks (the assemblies of individuals or entities) and institutions (what those assemblies do) can be difficult to define. One specific and relevant hard institution is the regular public attitudes tracker, undertaken on behalf of the UK Government [161], which provides quantitative information on public attitudes to energy options.

"Soft institutions"

Soft institutions relating to legitimation are the cultural norms which inform how opinions are formed and maintained. These include very wide-ranging cultural factors, such as the general belief in what one reads in the press or consumes in the mainstream media and trust in politicians and the media to tell the truth.

While the exploration of these norms lie outwith the scope of the current research, it is clear that the continuing existence of these norms is required for legitimacy to be expressed and maintained.

5.8.2.3 Networks

The general public and its relationship with the emerging TIS is a critical network in the legitimation of offshore renewables. The stance of the general public (and electorate) towards offshore wind and marine renewables is important in maintaining governmental support and funding, and the media play an important part in informing and influencing opinion within this network.

The networks at work in this sector are widespread and include the membership of the industry associations, relationships between technology developers and universities, the participants in the ORE Catapult's Cost Reduction Monitoring Framework. These networks are fluid, forming and dissolving in response to the needs and pressures of the sector.

To give an example, the ORE Catapult Cost Reduction Monitoring Framework, having concluded its work (and having helped offshore wind achieve a LCOE target of £100/MWh), disbanded [162]. SO34 explained that its work was complete and it had delivered the cost reductions required:

> *"Well it's done now - they don't need it." – SO34*

Conversely, the Marine Energy Council, recently formed by "a group of leading participants in the UK wave and tidal energy sector" [163] has been formed to make a case for financial support for wave and particularly tidal stream energy. Its report, UK Marine Energy 2019 – A New Industry [163] explicitly seeks to build legitimacy for tidal stream and wave by explaining the wide ranging benefits, including employment and export potential as well as low carbon energy that these technologies can provide.

5.8.3 Metrics, indicators and drivers

Metric / Indicator / Driver	Offshore wind	Comments	Marine	Comments
Numbers of interest groups and members	Some	Active interest groups and networks helping industry collaborate to reduce costs	Limited	New Marine Energy Council aiming to build legitimacy
Lobby actions by interest groups	Few	RSPB action against Mainstream's NnG wind farm a	Few	Very little activity in the sector, activity

		good example of interest groups attacking legitimacy		often in remote areas
Regulatory acceptance	High	Widely accepted as a key part of the UK energy mix	High	Regulatory framework well established, but few projects coming forward
IP protections	Good	Mature technology with development by large, well-financed companies	Good	Marine industry has been very focussed on IP protection
Political consistency	High	Government support for offshore wind co-evolved with technology	Low	Government support has been poorly aligned with technology needs
Trust and risk tolerance	High	Maturity of technology	Low	High profile failures and over-promising have undermined investor trust and appetite for risk

Table 5-14: F7 metrics, indicators and drivers: offshore wind and marine (author's analysis)

5.8.4 Validity

Legitimation was widely recognised to be a valid function in the evolution of the TIS. The average score was 3.14 with a standard deviation of 1.20. Although this was the second lowest score among the seven Hekkert functions, it is still indicative of the validity of the function.

Subjective comments explicitly in support of the validity of the function included:

> *"I read that most of the tidal developments have had environmental groups in opposition to them. I read that most of the wind farms have got environmental groups in opposition to them. I read that most of the oil and*

gas developments have got environmental groups in opposition to them. ***I think how you manage people's expectations is quite important.****" - MTD22 (author's emphasis)*

"There was a big media campaign in the autumn, round about the time of the CFD announcements, various media personalities. Peter Capaldi did an advert which was all over the London tube about the cost and the benefits of offshore wind. ***And so yeah, I think it's a driving factor. It's an enabling factor.****" – SH43 (author's emphasis)*

"But the funny thing is for us who work on projects, it's extremely important, so we put such a high degree of attention on it and actually diverts a lot of resources to legitimatizing our project." - WPD5

"I think the impact on tidal is less, clearly, than onshore wind, but ***I think it's important to have that social support.****" – MPD59 (author's emphasis)*

*"****So I think that it's very important*** *but I think offshore wind has kind of gone under the radar." – SO74 (author's emphasis*

Other comments implicitly recognised the importance of legitimation, by expressing the value of having public support or the validity of the question of social licence to operate:

"I think when we come to public acceptance and those kind of things, and obviously that's incredibly high for offshore wind, so I think the argument has been won." – WTG12

"Do you as an industry, any industry, need a social licence to operate in order to grow?" – PM29

In some cases, the negative power of a lack of legitimacy were described, again supporting the validity of the function:

"I think that if you rely on people liking it to develop it, you're on a hiding to nothing." - MTD22

"Once again, it can prevent a project going ahead on a micro scale, but on a macro scale I don't think it matters that much. I know that people adore what we did. We had 7000 letters written into the relevant minister, and it didn't make any difference." - MPD24

"I suspect for wave, it couldn't endure another one of those things [a failure] as it has a very tarnished reputation." – PM30

The lowest scores for legitimation were accompanied by the following comments:

"If you look at the industry as a whole, I think it [legitimation] would certainly make things easier." – WPD5

"Offshore wind seems to be popular with the voters at the moment." – PM49

"It's in our interest to make sure it's happening." - WPD1

These comments appear to support the importance of legitimation for the sector and are not considered to invalidate the function.

5.8.4.1 Sectoral analysis

Figure 5-18 shows the average scores for F7 – Legitimation by respondent group.

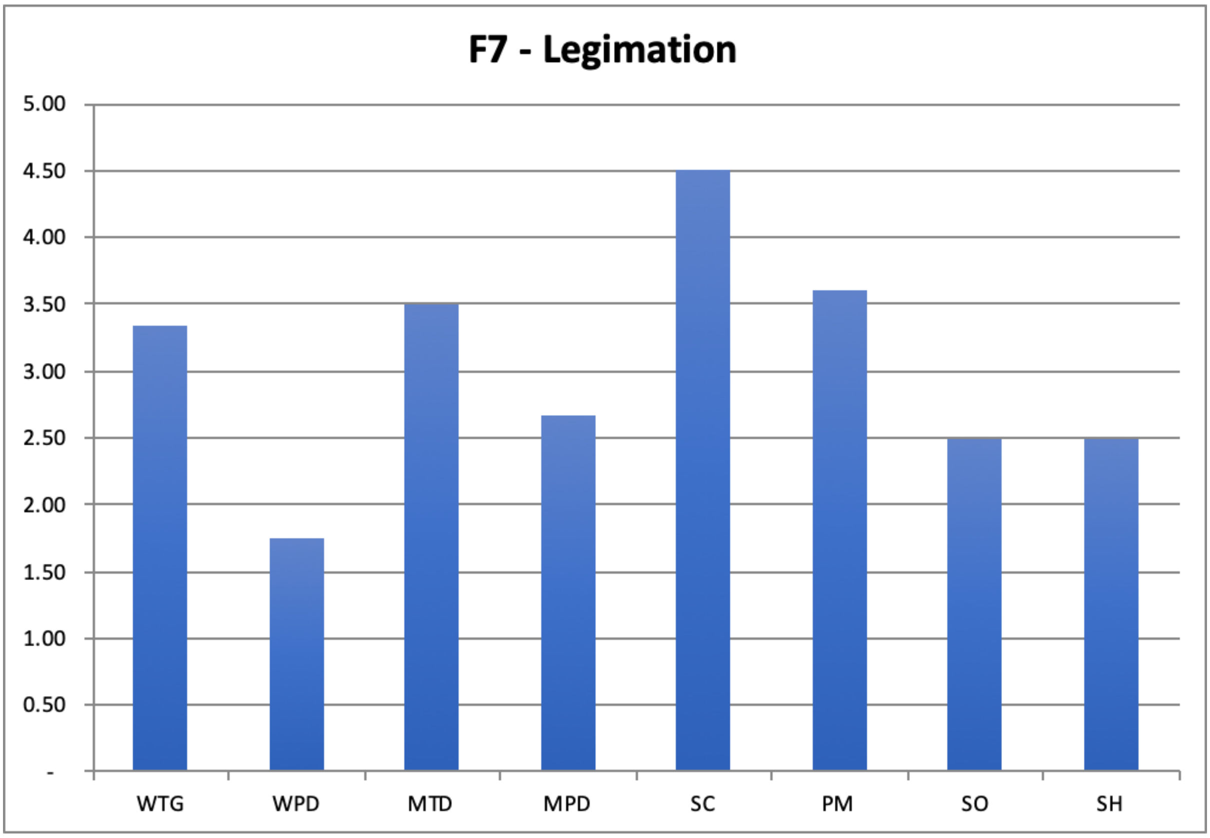

Figure 5-18: Analysis of F7 – Legitimation by respondent group (author's analysis) ; Key - WTG – Wind Turbine Generator Manufacturer; WPD – Wind Project Developer; MTD – Marine Technology Developer; MPD – Marine Project Developer; SC – Supply Chain Participant; PM – Policy maker; SO – Support Organisation; SH - Stakeholder

5.8.5 Conclusion – F7 - Legitimation

The validity and importance of F7- Legitimation was supported strongly by the results of the interviews, although it was noted that the legitimacy of offshore wind compared to tidal stream and wave was clearly more developed.

5.9 Relationships between functions

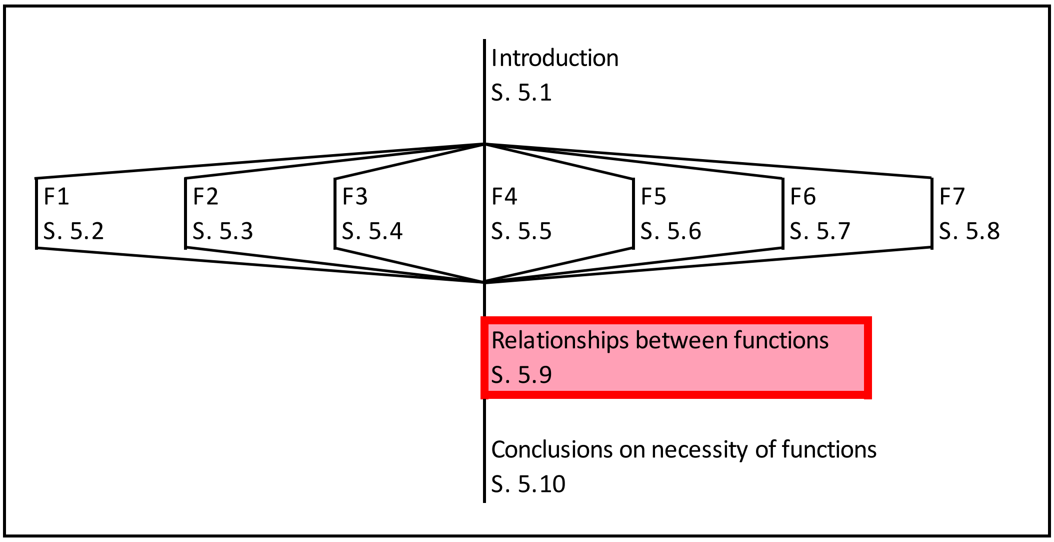

Figure 5-19: Section 5.9 roadmap

Analysis of the interviews confirmed the validity of the seven Hekkert functions. It also revealed operational and temporal relationships between the functions, which are explored further in this section.

5.9.1 Operational relationships between functions

The interviews revealed that there were operational relationships between many of the functions, as set out in Table 5-15 which shows the effect of each function on the others, with colour-coding giving an indication of the strength of the effect (green - high, amber – middle, red - low).

	F1 – Entre-preneurial Activity	**F2 – Know-ledge Develop-ment**	**F3 – Know-ledge Diff-usion and Net-working**	**F4 – Guidance of the Search**	**F5 – Market Form-ation**	**F6 – Resource Mobilis-ation**	**F7 – Legiti-mation**
F1 – Entre-preneurial Activity	NA	F1 inspires and often funds early knowledge develop-ment	F1 creates a network of know-ledge develop-ers amongst whom diffusion occurs	F1 can provide input to policy formation	F1 can inform incentive design	F1 has limited effect on F6	F1 creates early legitimacy
F2 – Know-ledge Develop-ment	F2 reassures entrepren-eurs of a	NA	F2 creates knowledg e for diffusion	F2 provides know-ledge for	F2 informs incentive design and potential	F2 has limited effect	F2 creates found-ation around which

	route to success			policy making	scale of market		legitimacy can develop
F3 – Know-ledge Diff-usion and Net-working	F3 allows for early learnings to diffuse, providing reassurance	F3 enables faster knowledge development	NA	F3 supports policy making	F3 enables widespread apprec-iation of market potential	F3 has limited effect	F3 creates wide base of know-ledge to support legitimacy
F4 – Guid-ance of the Search	F4 provides direction and incentive for entre-preneurs	F4 drives direction of knowledge develop-ment	F4 has limited effect on know-ledge diffusion	NA	F4 critically drives market formation and incentive design	F4 gives resource providers confidence in policy support	F4 provides "official" legitimacy
F5 – Market Forma-tion	F5 provides prospect of financial reward for entre-preneurs	F5 incentivises knowledge development and defines the market	F5 supports diffusion by creating market pull	F5 closely inter-related with Guidance of the Search	NA	F5 defines the market giving providers confidence in market finances	F5 defines market incentives, support-ing legitimacy
F6 – Re-source Mobil-isation	F6 generally takes place later than F1	F6 generally follows F2	F6 generally follows F3	F6 demon-strates industry confid-ence in sector, driving policy support	F6 confirms industry confidence in market, confirming market validity	NA	F6 shows that industry and investors are ready to commit to the sector, giving legitimacy
F7 – Legiti-mation	F7 provides reassure-ance for entre-preneurs	F7 provides confidence for researchers	F7 justifies diffusion of know-ledge	F7 validates support-ive policy formation	F7 justifies market incentives	F7 encourages resource mobilis-ation	NA

Table 5-15: Operational relationships between functions (author's analysis)

5.9.2 Temporal relationships between functions

Section 5.9.1 identifies operational relationships between the functions, and hints at temporal relationships too. This section sets out the strongest apparent temporal relationships between functions in the case of offshore wind in the UK.

These are set out in Figure 5-20, which shows an interpretation of the temporal relationships between the functions with an explanatory key.

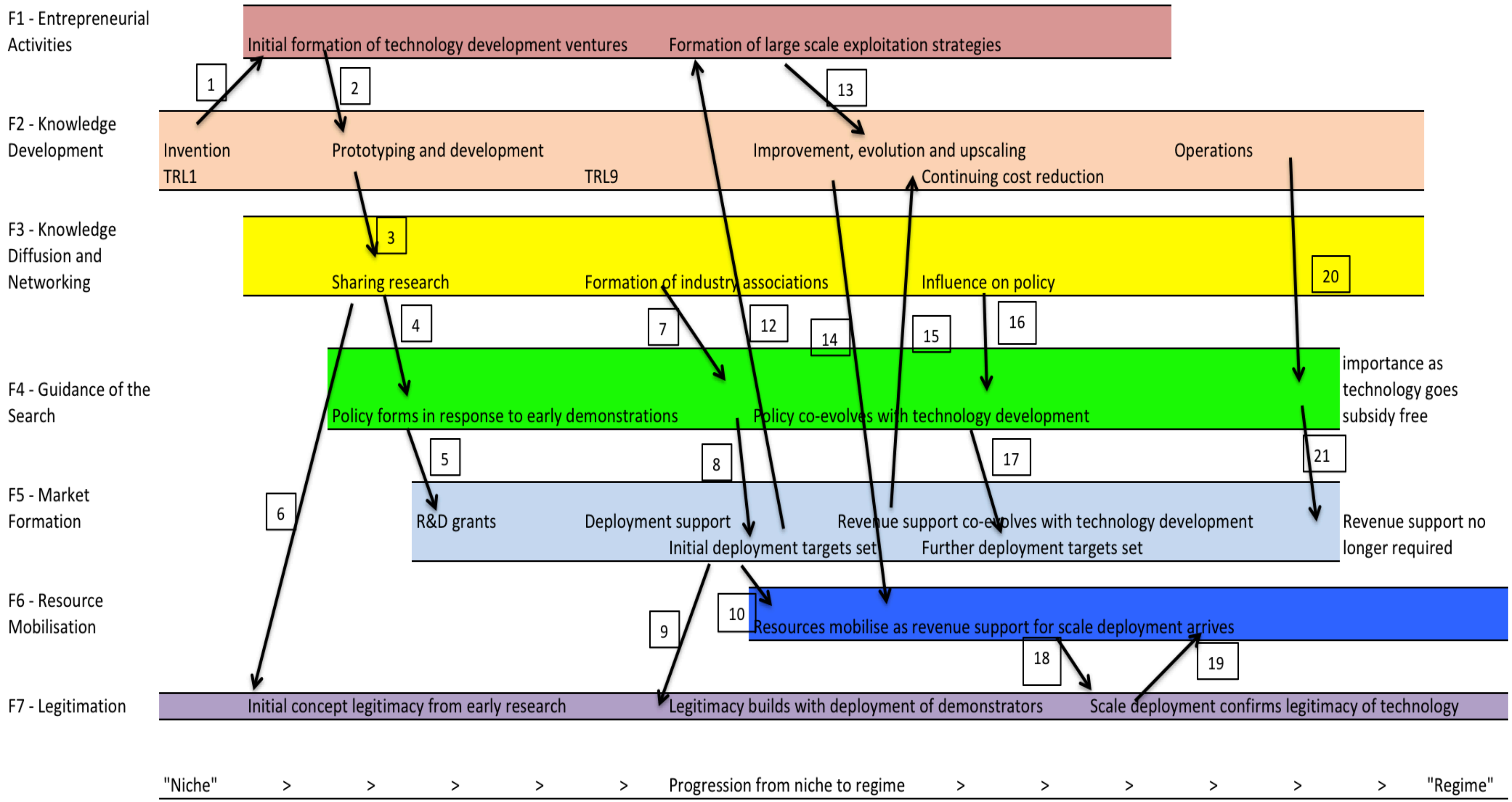

Figure 5-20: Temporal relationships between functions (author's analysis)

1. Initial invention leads to entrepreneurial interest (in the case of offshore wind, the demonstration of offshore potential using onshore technology)
2. Entrepreneurs sponsor fundamental research
3. Initial research is shared and networks start to form
4. Research networks begin to influence policy
5. Policy responds by making research and development grants
6. Early research, shared by networks, begins to build legitimacy for the concept
7. Industry associations form and begin to influence policy
8. Policy drives initial target setting
9. Initial targets contribute to growing legitimacy
10. Initial targets stimulate resource mobilisation
11. Building legitimacy encourages resource mobilisation
12. Initial targets stimulate formation of large scale exploitation strategies
13. Large scale ventures sponsor continuing technology upscaling
14. Visibility of technology upscaling further encourages resource mobilisation
15. Revenue support co-evolves with technology to keep driving development
16. Networks continue to influence policy development
17. Policy develops and further targets are set
18. Further targets further increase legitimacy
19. Legitimation through delivery further encourages resource mobilisation
20. Continuing cost reduction through innovation takes technology subsidy free
21. Change to subsidy-free policy changes/removes support scheme

5.10 Conclusions on necessity of functions

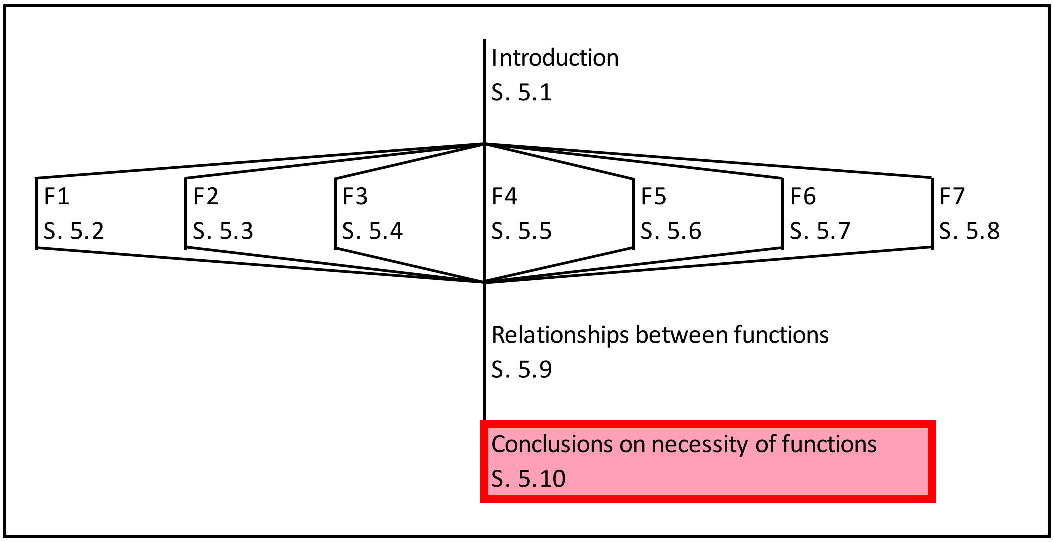

Figure 5-21: roadmap Section 5.10

The detailed analysis of more than 30 interviews with a wide ranging sample of participants in offshore wind and marine renewables has confirmed the validity of the seven Hekkert functions in the case of these emerging technologies.

Interviewees' qualitative comments and quantitative scoring strongly suggested that each of the functions was necessary for the evolution of the TIS. The interviews suggest that each of them has been executed and has contributed to the development of each of offshore wind, tidal stream and wave energy to their current state.

It was beyond the scope of this research to attempt a quantitative assessment of the functions, but the interviews analysed in this chapter confirm their necessity in assessing and examining the evolution of a TIS.

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6 Exploring the sufficiency of TIS functions

> *"Offshore wind is almost the worst thing that could have happened to wave and tidal." - SC56*

The review of the interviews confirmed the necessity of the seven Hekkert functions, as described in chapter 5. This chapter explores the question of whether these seven functions form a sufficient framework to describe a technology transition.

6.1 Review of interviews

The review of interviews in Nvivo (as described in Section 3.5.5) found that many interviewee comments did not fall cleanly into "nodes" defined for the seven functions but involved additional themes. During the analysis, it was found that all of the interviewees made substantive comments regarding the potential or actual economic, social and environmental contribution of the emergent technologies relative to both incumbent and other emerging technologies. This section explores those comments, to establish whether a unifying theme indicative of a new potential function was expressed.

6.2 Key themes

In the interviews, there emerged a number of key themes which were both substantive and not adequately or fully captured within the seven Hekkert functions. The first of these was motivation: the question of why participants in the emerging sector chose to become engaged in that sector.

The question of motivation rapidly moved to a discussion of cost reduction as a driver of competitive potential, and the differences between offshore wind (which was seen to have already demonstrated very significant cost reduction) and marine (which recognised the importance of achieving it but had so far failed to do so) was noted. The discussions also noted the important role of government, and the requirement for policy and support mechanisms to co-evolve with the technology, to maintain alignment and ensure adequate, and not excessive, returns for early adopters of the new technology.

It is necessary to specify the market in which the technology intends to operate before being able to evaluate the costs at which subsidy-free operation is possible. This was another theme which emerged, with one marine developer explaining that it had specifically opted to address a smaller but less price-sensitive market than the majority of its marine competitors:

> *"We spent a lot of time looking at the journeys that everybody else had, and [asking] "was there a different way of doing it?". I guess we saved a huge amount of money by looking at what other people did and then not necessarily starting down the [same path]". – MPD64*

This touches on the theme of "too big, too soon" as described by MacGillivray [71] and is addressed in Section 8.5.1.4.

The reality of competition with incumbent technologies (defeating "lock-in") and the race down the cost curve against other technologies were also described (e.g. by PM55).

> *"But it shouldn't be doing so at the expense of other sectors which might be more commercially viable..." – PM55*

The importance of scale was also touched upon, and the potential value of other benefits besides cost-competitive electricity generation were explored. Finally, differences in the potential pathways to market deployment for offshore wind and marine renewables were explored.

6.2.1 Motivation – financial return and other factors

The review of the interviews identified a number of motivations for taking an interest in an emerging renewables technology. Dominant among these was the opportunity to make a financial return on an enduring basis in a business stream that was aligned with the company's existing core business and/or stated strategy.

Wind project developers made this clear with a number of comments:

> *"We were sharpening our pencils because we wanted to make as much money as possible." – WPD1*

> *"We thought we could get them [the projects] away profitably. – WPD1*

"I think you can't get away from the fact that unless you can see a maturing profit stream in the timescale that you want out of these technologies, they are not going to be invested in." - WPD63

"So for the globals to really take an interest, it's got to be to be seen to be a likely candidate for core business or something where they can make some money and then maybe pass it on." – SO77

When asked if the business strategy to pursue offshore wind was anything more than just "business as usual", one respondent expanded on their earlier comments, making clear that the profit motive was very strong:

"I don't think there's any magic there - just straightforward great business opportunity, let's go for it." WPD1

"It was more around: 'is it a scalable business that can be profitable? Is there a demand for our product that we can deliver profitably?' - and the answer to that was 'yes'." - WPD1

Policy makers saw the same financial priority:

"They [technology and project developers] are not just doing it for the good of mankind. They are doing it bring down their future costs or to increase their future revenue." - PM49

"But they wouldn't go for it if they weren't making money. But that's entrepreneurship - you're not there purely for the good of society." - PM49

"Why do companies take decisions? If they see a future in it." - PM55

"But at its base, at its core, taking it back to simple levels, it's all about economics." - PM55

"Decisions are taken for a whole range of different reasons, but it all comes back down to money." PM55

One of these policy maker's remarks acknowledged the potential for choosing business strategy at least partly because of "the good of society". Other respondents made similar comments, often in passing or dismissively, but it nevertheless recognises that the contribution of societal benefit was a factor to be considered. This theme of other benefits arising is considered further in Section 6.2.8.

Profit was not the only motivation for actors in the space - curiosity played a part for some participants:

> *"I wouldn't even necessarily describe the early activities as entrepreneurial. These were enthusiastic engineers, and academics in some cases, who just wanted to demonstrate that it could be done." – WTG15*
> *"A lot of people get the buzz out of creating some new technology but they don't want anything to do with creating a business" – MTD64*

The existential threat to a business from not investing in the decarbonisation opportunity was also a factor:

> *"If you want to be in the future of the big organisations, in whatever shape or form, you will have to be in the energy transition" - SO60*

The strongest motivator for the majority of participants, however, was the profit motive – both in offshore wind and in marine. When asked if it "*would it be fair to say that the that the high level motivation for the innovation and the creation of a marine project development company was to make money"*, one interviewee simply responded:

> *"Yes." - MPD24*

Summarising, it is clear that the motives of promotors of emerging technologies were strongly influenced by the prospect of a financial return, which in turn is driven by the potential value of the emerging technologies relative to incumbents.

6.2.2 Cost reduction and roadmap to delivery

The dominant financial motivation led to the next emerging theme: that cost reduction was critical to an emerging technology demonstrating a roadmap to subsidy-free participation in the broader sector in which it intended to compete (what Geels [82] would call "the regime"):

> *"So cost reduction continues. It has to and that's driven by competition and the technology that that competition is engendering." - WPD1*

In the case of offshore wind, cost reductions were seen to be occurring in capital, operating and financing costs:

> *"What's changed of course over the past few years is that enormous cost reduction has switched offshore wind from being a niche but expensive with green choice to actually being the cheapest way to do stuff…we've seen massive reductions in O&M, massive improvements in the installation times, significantly reduced cost of capital, better skills across the industry. So Capex has broadly stayed the same, OpEx has come down dramatically, and yield - the denominator of the equation - has gone up very significantly from the larger turbines. So pretty much every slice of the cake has gone in the right direction and that means that that cost reduction has been pretty spectacular." - WTG12*

> *"It's absolutely cost that's driving the bus." - SC14*

Cost reductions were seen to have been driven by the competition for revenue support imposed by the Contracts for Difference support scheme:

> *"UK government was under pressure from the UK public consumer to get cost of green energy down. The CFD was successful in driving competition to decrease cost of capital which was only possible because the timing meant that there was sufficient deployed capacity for the investment community to have confidence." - SH36*

Both offshore wind and marine respondents recognised the importance of demonstrating a roadmap to subsidy-free operation:

> *"I think you can't get away from the fact that unless you can see a maturing profit stream in the timescale that you want out of these technologies, they are not going to be invested in." - WPD63*

> *"The context now is you have to make electricity that is competitive to the consumer, and if it isn't on day one then create a storyboard and a line of sight that actually says it will be one day." - WTG15*

> *"There has to be a demonstration that there is a possibility of cost falls to bring it within that overall mission of cheap energy in the future." – PM30*

> *"If you can prove that in the medium term this technology (a) will work, (b) will be commercially viable and (c) will not require x amounts of subsidy over X amount of years in perpetuity, then I think that's probably the three tests that you have to pass." - PM55*

Another marine developer also expressed the need for a roadmap:

> *"So it's really important in wave and tidal. You've got a set up a clear vision about of how investment in the sector can make a return." – MTD58*

The impact of cost reductions in offshore wind on the potential value of other technologies was also explicitly recognised:

> *"I think that's where - because the circumstances of offshore wind changed it for everybody else - it would be really difficult for any other technology to come and sit alongside offshore, onshore and solar as large scale ways of making electricity." – WTG15*

> *"We've got offshore wind, we're getting fifty seven pounds fifty*[11] *- why would we need to pay 300 pounds per megawatt hour for a wave or a tidal? it sounds crazy but offshore wind is almost the worst thing that could have happened to wave and tidal." – SC56*

This is an important point: the performance (in financial or other terms) of competing technologies, whether incumbent or emerging, can significantly impact the viability of an emerging technology.

6.2.3 The role of government and co-evolution

As Section 5.5 made clear, the role of Government is critical in driving technological emergence. Interviewees considered it important that government policy evolves in line with, and in the light of, technological developments.

The general importance of government policy in creating a supportive environment for the emergence of the new technology was noted by a number of interviewees:

> *"You need the fiscal side to support that, the right fiscal framework and the long term policy leadership. And you then need the detail to support that." - MPD59*

> *"It sits with government policy because that's currently where we've made all those decisions under a policy heading." – PM65*

It was widely recognised that the government had to ensure the cost effectiveness of its spend:

[11] £57.50/MWh is the strike price for offshore wind projects in CfD "Pot 2" for delivery in 2022/23

"And decisions are taken for a whole range of different reasons but primarily it comes down to cost/benefit - bang for buck of in terms of taxpayers' money." – PM55

Interviewees focussed more on the negative impact of a lack of perceived value for money than on the positive feedback. For example, one supply chain participant noted this:

"And they said "because it's too expensive. The technology is too expensive and we think that the limited government funds are better spent elsewhere." - SC10

Others recognised that government support for other emerging technologies had fallen away as value for money was not demonstrated:

"I think there was a mistake in 2014 when George Osborne decided not to continue funding the carbon capture and storage program because he felt it wasn't, you know, commercially viable or of value to the taxpayer." - PM55

"And the Swansea Bay Tidal Lagoon was proven not to be worth it given the huge advances made in offshore wind." - PM55

Interviewees accepted that it was important for participants to demonstrate progress in cost reduction to maintain government support:

"So offshore wind has been so successful in reducing its cost to the consumer that the government is just jumping on that and can't see beyond it at the moment. And it's to the detriment of other technologies that feel that they have no way of competing because the technology is more expensive." – SC10

"And that's when the ORE Catapult started doing the cost reduction monitoring framework. That was monitoring effectively of the industry side of that bargain. Government were saying - "look you know you're telling us you going to get there (£100/MWh), but how do we know you're actually getting there?" – SO74

One support organisation interviewee noted that progress in one area, in this case offshore wind, could change the government's focus, to the detriment of other emerging technologies.

"And I suppose now that offshore wind is proving its ability to drive down costs, and there's a good healthy UK market for offshore wind - not necessarily with a big UK content - then I think the government are swinging towards they are keen on renewables but they set very clear tests now around the clean growth strategy in terms of what a new technology has got to be able to achieve. And wave and tidal wave are certainly struggling to match those tests, so it's become more difficult." – SO77

One additional factor influencing government support was the broader political perception of the support decision. One supply chain participant suggested that where support might have been terminated in a commercial environment, there could be wider factors driving government to maintain it:

"The reason it keeps going is either because there's an embarrassment factor, when in a commercial environment you'd just put a line through it." – SC20

A significant topic in the area of government support was the need for the support schemes to co-evolve with the technology, to ensure that the support schemes offered an appropriate return for the level of technology development and risk. This is potentially at odds with the need for stability expressed by one supply chain participant:

"I think it was something we were very concerned about early on when we were trying to go back into offshore wind. It was very much a government subsidized business. And Executive Management were always worried that if it's a government subsidized business and politics changes then suddenly you can lose your business overnight because the environment changes. And that's been a bit of a challenge and probably that's slowed investment in renewables." – SC14

This is generally dealt with by government grandfathering support schemes, and thereby enabling co-evolution of support and technology. Many interviewees noted the importance of change in the support regimes:

"I think it's important that you have the right support for development." – SO32

"The ROCs scheme seemed to work well for those initial projects, it got the ball rolling. The CFD is more of a response to political pressures to ensure the entire system is developing more value." - SH43

"The CFD might come to an end eventually because these projects are cheap enough they don't need any assistance in any way." - PM49

Some participants expressed the view that misalignment between support schemes and technology readiness could lead to technological development stalling or ceasing altogether:

"And so things like the MRDF, which was a capital grant scheme that was coupled with five ROCs at the time for wave (and three for tidal) was a really attractive regime. The problem was: they didn't need it yet and they were still delivering single devices. So they then rushed to the first farm stage and had a nightmare, as was to be expected, and this was all because they'd kind of overpromised. And so in terms of policy support - it was actually a great policy support mechanism for a while, but they just weren't ready for it." - SH40

One marine project developer outlined the approach the marine sector has adopted to attempt to "reboot" support for this sector:

"They've agreed on the route through, so you have an IPPA to start with, which is incremental, you then get into ICFD or pot 2B or whatever you want to call it. And then we become competitive - competitive with other comparable forms - so we imagine that floating wind and tidal would be very competitive in the same space at the same scale of projects over the same time scales." - MPD72

The co-evolution of technology and policy helps to maintain an appropriate reward structure for emerging technologies.

6.2.4 Route to market and choice of market

As Section 5.6 describes, the formation of a market for the emergent technology is critical to its widespread adoption. The aim of parity with existing large scale generation technologies was explicit for the sector:

"The market that's coming now is coming later which is basically saying it's an open market and we can compete with any other form of energy on it." - WPD7

The clear expectation amongst offshore wind was that large scale market mechanisms, such as carbon pricing, would emerge to ensure that offshore wind could play a significant part in the UK energy mix and to help this emerging technology on the journey.

> *"So it depends on your carbon price view doesn't it? So given the price of coal, if you add unabated coal with no penalty for pollution that's always going to be very very cheap. So it really depends what playing field you want us to compete on." - WPD1*

It was noted that another way of making the evolution to parity with existing grid sources might involve accessing nearer term markets in which a higher price point was acceptable:

> *"There is a lot of interesting technology out there that is not utility scale, it's off-grid, or it's remote islands…the money is a completely different." – SC14*

The virtuous circle, in which increased deployment leads to reduced costs and hence further deployment, was seen to be a route by which the market could emerge:

> *"So, thinking about offshore wind for a moment. I think what happened there was the market size got interesting. People realized 'well actually we could make some money out of this'. So you started seeing utility companies get serious about project development. So I think once these companies realize that this was a credible commercial proposition, you've got the market pull there and you then start being able to create the pull for technologies to come through." – SH40*

While all participants in offshore wind were targeting the utility scale multi-MW project, some participants in the marine sector recognised that other markets might offer a higher price. The market for small scale diesel generation, which has a much higher cost than large scale grid electricity, was one example cited:

> *"So, the idea of building lots of small turbines, understanding what your issues are and then scaling it - I think that's okay. Especially where you don't have the policy support mechanism anymore. So you've got to try and look for markets where you displace diesel or something." – SH40*

One Marine Technology Developer explained that this recognition lay at the core of its strategy, which relied on monetising these higher price niches.

"By finding commercial applications that on their own merits, without any government incentives...Basically, it was 'if it needs government incentives to make it financially viable in a project, then don't go for it'." - MTD64

In all of these cases and observations, the market or the potential for a market to develop was seen to exist (or not) in the context of the competing technologies, and this is central to the new function.

6.2.5 Competition with incumbent technologies

Hekkert et al. [95] described "lock-in" as "inertia of technology-innovation systems" which results in "relatively rigid technological trajectories". Others including Walz [164] note that lock-in is encouraged in systems with long-life assets: inevitably the operators of incumbent technologies are motivated to resist change and maintain lock-in.

The interviewees recognised this tension between incumbent and emergent technologies, in which incumbent operators have little incentive to encourage emergent and competitive technologies. Despite this inertia, developers of offshore wind projects and their supply chain recognised that the competition with incumbent technologies was winnable:

"There's one major reason why offshore wind is so competitive now. Beyond the wildest dreams of anyone five years ago - is competition and the CFD process." - SC10

"And of course that's really transformed the approach not just for offshore wind but for all of the other sectors as well. So it's a massive challenge for nuclear. It's a massive challenge actually for new gas plant, which all of a sudden isn't the obvious cheap option." - WTG12

"We put together a framework when we were thinking about the tidal wave accelerators and the offshore wind accelerators - and there were four components of that framework…One was about getting the market dynamic right - whether it's feed-in tariff, Renewables Obligation - what's the pull mechanism? The second was the regulation - so interconnectors, planning permission, all the things that might slow up. The third was what I'll call the competitive dynamic around how competitive was the technology to the incumbent? So the cost curve and learning curves. So how quickly could...taking the component parts of this technology, imagining it at scale and doing the engineering studies that said could it ever be cost effective." – PM29

"And where we are with offshore wind, as a technology which is now cost competitive with new gas, based on the auction prices and can deliver at GW scales and in the same locations that wave would (not tidal – tidal is more constrained). Then yeah, you need variety, variety in your generation but that's all you need." - SO34

Developers recognised too that their investments had to compete for capital both within the firm and more generally across investment markets:

"When they go into the boardroom, they have to make a case for capital against another director who is making the case to go exploring new oil wells or to refurbish a rig or whatever it might be, and so at the end of the day, money is money. And you are competing in that?" - SH40

One wind turbine generator manufacturer acknowledged that their call on Government's limited funding capacity did not just compete across the energy sector, but more widely with general spending needs:

"That is what is happening. When you're sitting there and you're going to look at whether to allocate funding towards measures to reduce the cost of energy in the UK or allocate it to schools or hospitals. Why would you spend money on technology that when you see the cost of energy is already down sufficiently?" – WTG78

The competition between offshore wind, marine renewables and nuclear was raised in a number of interviews, with the general feeling being that nuclear represented a poor use of funds, but that it was important that commitments that had been made should be adhered to:

"Does Hinkley Point meet the three tests that Claire Perry set out? - no, at the minute it probably doesn't. Which is why a lot of people have been asking a lot of serious and genuine questions around the viability of the Hinkley Point C. But as I said, contracts have been signed, a lot of money has been spent, and therefore Government can't really get out of it." – PM55

"It does get interesting, you're right, I think there's merits, given the socio economic benefits we were talking about of a UK industry relative to nuclear again." - MPD59

The oil industry might seem to be the obvious source of investment funds for offshore renewables project development, as its technological skill set of developing, operating and maintaining large installations in challenging marine environments, such as the North Sea. While interviewees recognised this, and in some cases, some of these operators are taking an increasing interest, the different financial profile of offshore wind relative to oil development was seen to be a hurdle:

> *"And in the end, what destroyed everybody's ability for the oil companies to come in is you could see the oil price booming and you were basically how could wind farms compete and let's be honest, wind farms are actually largely long term saved energy sources and they are going to return 8-9 percent, you know. They're never going to return 20-22%." WPD7*

The competition with incumbent technologies and other investment opportunities was ultimately seen as a quest for parity with other sources of generation.

> *"I think the challenge is how do we make wind on par with other energy sources and the true innovation has been in terms of the efficiency, the cost effectiveness of it, to make sure there is parity between that and other energy sources - I think it's driven by some of the big with developers going down the efficiency curve." - SO60*

The quest for parity, which by definition takes account of the cost of competing technologies and the likely trajectories of these technologies, was seen to be a key factor, and this forms part of the new function as defined in Section [ ].

6.2.6 Competition between emergent technologies

A recurring theme when considering the interaction between the different emerging technologies was that "the winner takes it all". The success of offshore wind in drastically reducing costs, coupled with its large available resource, were perceived to make a compelling case, and to undermine the case for investing in competing, but functionally equivalent, technologies (functional equivalence is discussed in Section 7.1.1).

Two wind turbine generators provided some context for this challenge for the lagging technologies:

> *"And for wave and tidal and some of the emerging technologies. It's an even bigger challenge because the argument that 'you have to fund those expensive things so you make it cheap' of course worked for wind...it's now very difficult to see how other technologies following along behind will be able to benefit from the same process, because unless you actually believe that they're going to get cheaper than offshore wind there's a big question as to "why do you need more than one kind of winner?" - WTG12*

"I think that's where the - because the circumstances of offshore wind changed it for everybody else - and it would be really difficult for any other technology to come and sit alongside offshore, onshore and solar as large scale ways of making electricity." - WTG15

"So it, I said that there has been a great stepping stone to get the industry to where it wants to be, but that's potentially now at the detriment to newer technologies like floating, like wave, like tidal." - PM49

"Some people will argue that you need to be putting money funding investment into wave and tidal - that's how offshore wind got to where it got to, you know you've got to do the same- but the counter argument almost with that now, is that we've had a lot of enablers say "well, if we've got massive untapped potential on global offshore wind, why do we need...[wave and tidal]" – SC56

Other technologies were also seen to be disadvantaged by the cost reductions achieved by offshore wind. For example, the proposed Swansea Tidal Lagoon's high cost base was seen to make development support unjustifiable:

"And the Swansea Bay Tidal Lagoon was proven not to be worth it given the huge advances made in offshore wind." - PM55

In addition, one research participant suggested that the apparently high cost of carbon capture and storage led the government to withdraw support as offshore wind represented a lower cost carbon abatement option:

"I think there was a mistake in 2014 when George Osborne[12] decided not to continue funding the carbon capture and storage program because he felt it wasn't, you know, commercially viable or of value to the taxpayer." - PM55

In summary, there was a view that while tidal stream and wave could be made to be technologically viable, it was no longer possible to justify the investment required to make it commercially viable:

"I think there's a genuine feeling that there is a free and easily accessible resource in wave and tidal, and it feels like a fairly obvious challenge that you should be able to capture that resource, and in the first instance it would seem relatively straightforward to be able to do that. And I think the reality then is that we know we can capture energy from waves, we know we can capture energy from the tide. We know we can then connect that

[12] George Osborne was Chancellor of the Exchequer in the UK Government in 2014

up to the grid and put energy onto the grid. So we've done that. What we can't do is make that cost competitive." – SO77

6.2.7 Scale

A number of interviewees referred to a perceived virtuous circle in which scale and technological development fostered one another. This relationship was described by a number of interviewees.

> *"I think techno-economic viability - when you get to commercial scale that's very important." - SC14*

> *"So we've been able to really take out some of the cost on the O&M side and the scale of the projects now, going from 50 to 100 MW now to 500 to 1000 MW. Obviously that scale gives you gives you purchasing power." – WPD5*

> *"My take on it is that the offshore wind journey has been very much driven by utility scale and organisations of that kind of nature. We talked earlier about access to capital. It's been people who can see an endgame that's worth funding." - SO75*

> *"If no-one standardizes anything and you get to 300 MW and still everyone looks completely different in every way, then that isn't going to be very helpful because you haven't deployed 300 MW, you've probably only effectively deployed 30MW of each type, so the learning opportunities aren't maximised." – SH40*

One marine developer also described the advantage of offshore wind relative to the marine sector, as offshore wind had achieved scale effects, while marine had yet to do so:

> *"So they knew that they could get the technology to scale. They found a route to do that, and that drove the investment back into the technology itself." - MPD72*

One stakeholder put the scale challenge for the marine sector relative to offshore wind more soberly:

> *"I'm not entirely sure I'm ready to say that these technologies were never going to work; I think I might be ready to say that wave technologies at utility scale - certainly the scale we're talking now were never going to work, I may be prepared to say that." – PM30*

The effect of scale was clearly seen to be beneficial to the development of the technology, and this again contributes to the "winner takes all" aspect of the competition between functionally equivalent emergent technologies.

6.2.8 Financial returns and other benefits

As Section 6.2.1 made clear, the financial motivation was strong for most participants in the sector. However, the interviewees recognised that other benefits besides the financial return could affect the competitive positioning of competing technologies.

Firstly, one policy maker directly introduced the concept of other (potentially non-financial) benefits into the conversation:

> *"If they were both the same price, why would you use one technology over the other?" – PM49*

The marine sector has specifically taken this idea on board, as it recognises that its competitiveness on purely cost grounds is inadequate and that it will need to make a case based on wider contribution to the economy, specifically in terms of high quality jobs:

> *"Our argument is that the cost curves come down much faster than wind or solar ever achieved but **it will be a domestic industry which actually is generating the very middle to high class engineering jobs** that everybody is hoping will actually occur in the manufacturing sector that's going to be decimated by Brexit." - MPD24 (author's emphasis)*

The interviewees identified potential additional benefits in a number of areas. The lower pollution and environmental benefits attributed to renewables, as well as reduced exposure to fossil fuel prices, was one:

> *"You're absolutely right that this was all part of the response to pollution from coal burning and from oil. However, I think the bigger impact was the huge hike in oil prices in the early 1980's. And if you looked at how oil prices had driven up - I mean in the North of Scotland, they had to put surcharges on customers' bills to cover the extra cost of oil, because most of the generation other than hydro was oil-based. Huge investments in oil-fired plants throughout the UK became uneconomic very quickly and were ultimately abandoned. Nuclear was seen as the better alternative to coal and interest in renewable sources was also engaged." - WPD63*

The creation of local jobs and contribution to the United Kingdom's Gross Value Added was widely seen to be attractive:

> *"There's a dilemma between UK content and low cost. Government is very keen to push up the 50 to 60 percent UK content, but at the same time the developers only care about lowest price." – SH40*

However, as one marine project developer pointed out, there was not always a reward for these additional benefits:

> *"The two big arguments we had over the CFD - there is no reward for ancillary benefits…obviously your domestic support chain - there's no rewards for that, so there's no incentive to try and build British." MPD24*

Part of the GVA offering was recognised to be export potential, particularly for the wave and tidal stream sectors where securing device manufacturing for the UK was seen to still be a winnable battle:

> *"So I think, you know, if we continue, and we can maintain the lead in this, and we can get some devices that prove technically possible and that can show that they can reduce their levelised cost - they can reduce their unit cost of energy - there is potentially manufacturing - manufacturing and export - huge export potential for Scotland." – PM65*

And finally, the benefits to grid stability from a multiplicity of generating sources was also seen to be a societal benefit (even if, as previously noted, it was not necessarily rewarded):

> *"There is no reward for ancillary benefits (because we're predictable, we've got a lot of different attributes, we can obviously provide for grid stability) - you don't get paid for that, and predictability - you don't get paid for that." MPD24*

6.2.9 Differences between offshore wind and marine

The final key theme which emerged in the interviews was the difference in competitive positioning and potential between offshore wind and marine. While offshore wind was seen to have achieved very significant cost reductions over the period since 2000, the marine sector felt that its technologies could be capable of achieving a similar trajectory if they received similar support:

"People like Simec Atlantis are saying 'yes, but where was offshore wind 10-15 years ago?' and 'it had an enabler through ROCs to develop its technology and become more competitive. And then it had an auction to even drive that cost and that competition even more - why can't we have that same opportunity?'" - SC10

"I think that the response to that from me and from the industry is 'no, we've got to try and persuade them to put the incentives in'. They've done it for virtually every other new industry, why shouldn't they do it for wave and tidal, just because it's further away?' - SO37

Participants representing the wind turbine sector accepted this argument, but asked why marine should be supported, since offshore wind had already achieved the necessary cost levels:

"There's only room for so many and I can see that the proponents of wave and tidal find that hard to swallow - to say we shouldn't invest in those early stage expensive technologies when that's exactly what happened with wind. But it's a problem we only have to solve once really, it's where are you going to get cheap low carbon energy from?" - WTG12

"And for wave and tidal and some of the emerging technologies. It's an even bigger challenge because the argument that 'you have to fund those expensive things so you make it cheap' of course worked for wind…It's now very difficult to see how other technologies following along behind will be able to benefit from the same process, because unless you actually believe that they're going to get cheaper than offshore wind there's a big question as to "why do you need more than one kind of winner?" – WTG12

The marine sector has been buoyed by a recent report by the Offshore Renewable Energy Catapult [150] which suggests that cost reduction sufficient to make marine technologies competitive at least with nuclear should be readily achievable in the near term:

I think so, look at the Catapult report, with contributions from across the industry, and the industry is broadly aligned with what the Catapult is saying. You can see cost reduction coming in fairly quickly. They're talking about a GW - which I think is good, if you get into that territory (under £100/MWh), it puts it on a par with new nuclear." - MPD59

On that basis, the marine sector is beginning to believe that it can set out a persuasive roadmap, although the challenges are clearly perceived:

"So it's really important in wave and tidal. You've got to set up a clear vision about of how investment in the sector can make a return." – MTD58

The cost challenge, especially for wave was recognised too:

> *"Wave is interesting because technically it's quite an interesting challenge but also because the potential is enormous. There's an awful lot of ocean out there that you could generate electricity off. So the upside is quite exciting but the technical challenge are significant. Wave has some really big challenges: can we ever get the price down low enough? And those things are not really compatible: if you make it robust enough to survive the extreme one, then it costs too much." – SC14*

WTG15, when it was suggested by the researcher that it appeared that cost reduction in offshore wind had moved the goalposts for wave developers so drastically that they had been slightly stymied", agreed that that statement:

> *"summed it up very neatly." – WTG15*

Marine technologies also had a challenge delivering at scale, while offshore wind had succeeded in this:

> *"And obviously if you couldn't do it at a gigawatt scale next year, it just wasn't interesting." - MPD24*

> *"I'm not entirely sure I'm ready to say that these technologies were never going to work; I think I might be ready to see that wave technologies at utility scale - certainly the scale we're talking now were never going to work, I may be prepared to say that." - PM30*

The marine sector recognises that offering attractive financial returns was essential to securing adequate capital funding. Interviewees had few positive comments on the success of the marine sector in attracting this funding. Some of the failure was a result of early, aggressive promises made to venture capital investors by developers:

> *"With wave and tidal, I think what's happened is the industry have had to be fairly bullish to secure their investments from...certainly from the private sector, they've had to promise a lot." – SH40*

The majority of negative comments around funding, however, compared the investability of the offshore wind sector with that of wave and tidal stream. One marine project developer felt that "the deck was stacked" against the marine sector:

> *"The deck was always stacked against whoever was going to compete against them [the offshore wind sector], primarily because the business model changed - it changed from being the most efficient machine to a being cost of capital fight." – MPD24*

A more even-handed view might be that the offshore wind sector successfully de-risked its technology to justify a lower cost of capital. Another interviewee offered a narrative of how offshore wind had outcompeted marine from similar starting points, as offshore wind had successfully achieved cost reductions, in part through technology convergence and volume, while wave and tidal stream had not. The same interviewee went on to explain that the support climate is now strongly focussed on comparative value, effectively disqualifying marine technologies:

> *"If we go back a number of years to when offshore wind had the opportunity to develop the technology and start high up the cost curve and come down, again if wave and/or tidal both either were there, in the same position [with] a reasonably converged design, and it was about testing the last issues and getting the volume and the cost reductions. They could all be in a very much different place whereas they're trying to start in in a climate where the focus is on 'if you're not value for money already, you've very little chance of getting your foot in the door'." – SO75*

Some interviewees simply questioned the rationale for investment in marine technologies, as offshore wind had already shown its capacity to deliver"

> *"I do not understand why anybody would invest in wave technology, because of what we've achieved in this industry [offshore wind]. I think we are we are really at the very very early stages of this. Very very early stages. But we don't need wave energy." – WPD5*

> *"I struggle to see how wave and tidal is going to attract the necessary money it's going to need - it needs step change, but it sounds crazy but offshore wind is almost the worst thing that could have happened to wave and tidal." – SC56*

In summary, one support organisation interviewee captured the essence of the new function, in noting that while there is technical potential in the marine technologies, the commercial challenge remains unsolved:

> *"I think there's a genuine feeling that there is a free and easily accessible resource in wave and tidal, and it feels like a fairly obvious challenge that you should be able to capture that resource, and in the first instance it would seem relatively straightforward to be able to do that. And I think the reality then is that we know we can capture energy from waves, we know*

we can capture energy from the tide. We know we can then connect that up to the grid and put energy onto the grid. So we've done that. What we can't do is make that cost competitive.” – SO77

6.3 Conclusions on sufficiency of functions

The analysis of the interviews found that multiple insights from interviewees met the criteria for a new function. Many comments did not naturally fall into the definitions of one of the Hekkert functions, but nonetheless described important themes in the evolution of the socio-technical system.

The next chapter describes those findings in more detail, and described the function whose definition emerged from this analysis of the interviews.

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7 Findings – a proposed new function

Chapter 6 described the observations which support the introduction of a new function. This chapter defines the proposed new function and explores how it might be evaluated.

It defines a new economic measure, Full Cost of Energy, which can account for externalities arising from different electricity generation options, and tests this measure in a comparison of offshore wind with a thermal generation option.

7.1 Functional definition

The interviews with stakeholders in the offshore wind, tidal stream and wave energy sectors revealed that the potential of these emerging technologies to operate without subsidy is a critical factor in considering whether they would successfully emerge and that the existing seven "Hekkert" functions did not adequately address this factor. The seven Hekkert functions, while necessary, were found to be insufficient to fully characterise the emergence of the TIS and a new function was required.

Accordingly, a new function – "relative value potential" – is proposed, to address this need.

The proposed new function of relative value potential is therefore defined as "the potential or actuality of the focal technology in the TIS being competitive with relevant incumbent or emergent technologies".

It is helpful to look at each part of this definition to obtain a full understanding of what is proposed.

"Potential or actuality" – the function addresses whether the focal technology in the TIS either has already or can potentially demonstrate a roadmap to economic or other competitiveness. The measures of this competitiveness are considered in detail in chapter 8.

"Competitive" – the focal technology in the TIS can make a case for existence without special treatment in the context of the technologies with which it emerges to compete (e.g. the emerging technology no longer requires a subsidy or offers other benefits).

"Relevant incumbent technologies" –existing technology or technologies which already operate without special protection in the broader technological field where the focal technology in the TIS exists (eg thermal power generation).

"Relevant emergent technologies" – any emergent technology or technologies which have the potential to compete with the focal technology in the TIS (e.g. wave energy technology competing with offshore wind energy technology)

7.1.1 Functional equivalence of offshore wind and marine renewables

Offshore wind and marine renewables share a number of characteristics which make them functionally equivalent in the context of contribution to the grid. Offshore wind and wave are most directly equivalent, with tidal having one key difference.

- Intermittency – all three technologies are intermittent with output not "dispatchable" to the grid in response to demand
- Marine environment – all three technologies operate in the marine environment, which makes particular demands in terms of reliability, maintainability, corrosion management and access
- Small individual generating units - offshore wind turbines have increased in capacity from less than 1 MW to nearly 10MW (and plans have been announced for 12 MW)
- Generating farms comprise multiple units – multiple units are required to build up a significant generating capacity, giving rise to logistics challenges
- Predictability – offshore wind and wave are not predictable over more than a few hours. Tidal is accurately predictable over all time scales

The functional equivalence of offshore wind and marine renewables meant that they faced similar challenges when they initially sought deployment opportunities.

7.1.2 Narrative of technology emergence – offshore wind vs. marine renewables

In 2000, both offshore wind and marine renewables technologies were essentially pre-prototype technologies, sharing an ambition to contribute to the UK energy mix at utility scale. At this point, the expected cost base of offshore wind was known, as the cost of deploying "marinised" onshore wind technology in very shallow water, nearshore environments was readily estimable. Wave and tidal stream technologies appeared to hold technical promise and to have potential for large scale deployment, with many technology developers at work with early prototypes.

The evolution of the sectors is summarised in Table 7-1.

Change to policy	Impact on offshore wind	Impact on marine renewables
The climate change agenda stimulated the evolution of offshore wind, wave and tidal	Developers marinised onshore technology in first offshore deployments	EMEC established as test centre for marine technologies
The Renewables Obligation was introduced to incentivise the roll out of renewables	The first offshore wind farms, with capacities of less than 100 MW were deployed	Early prototypes deployed at EMEC and elsewhere; wave leading tidal stream
The RO was banded, offering differential support to offshore wind, tidal stream and wave	Additional offshore wind farms were deployed, future rounds were announced	Continuing prototyping of wave and tidal; no clear performance/cost breakthroughs even in context of targeted support
Offshore wind near term target was set by government at £100/MWh with incentive of further wind farms	The offshore wind cost base appeared to be around £150/MWh in 2010, based on deployed base of 0.7GW [62,63]	Wave and tidal stream felt that they were at around £300/MWh, based on < 10 MW deployed; some marine company failures (e.g. Pelamis)
EMR and the withdrawal of RO changed the funding framework, aiming for cost effectiveness for consumers	Offshore wind engaged with cost reduction target through Cost Reduction Monitoring Framework	Wave and tidal felt that its cost reduction potential was stronger than for offshore wind ie: steeper learning curve potential to reach £100/MWh (parity with wind) in near term
Government commitment to Offshore Wind Sector Deal [47] confirms commitment to future wind farm support	Offshore wind bid into CfD Pot 2 at £57.50/MWh	Marine technologies stymied by change in target cost implied by offshore wind; withdrawal of some significant investors

Table 7-1: Competitive evolution of offshore wind and marine renewables (author's analysis)

To summarise, offshore wind achieved very rapid cost reduction, as described by one of the wind project developers:

“I would expect that both government and the industry as a whole has surprised itself on the cost trajectory that has taken place over the last few years" – WPD5

This very rapid cost reduction radically changed the competitive playing field for marine renewables, which had thought that it was aiming for a target cost of £100/MWh. When the sector found that the competitive technology had achieved cost levels of around half of this, the effect on many of the other seven functions severely impacted potential for marine. For example, the legitimacy of marine was affected as offshore wind was seen to be a more attractive solution. As a result of this shift in techno-economic context, the marine sector has pivoted away from defining the argument in its favour from one of cost, to considering the wider benefits of the technology.

However, the seven functions analysis failed to take account of this contextual change pointing out the need for the new function.

7.2 Is there room for a new function?

The application of functions within the TIS framework is revealing of many of the factors influencing the success or failure of transitions. However, this research into a specific technological evolution suggests that another function is required to more fully describe the success or failure of transitions.

As Borup et al. [165] note, the functions defined by Hekkert et al. [95], Bergek et al. [92] "overlap and should not be understood as mechanical building blocks". The definition of a new function will almost inevitably overlap with existing definitions in some areas and should not be undertaken lightly. However, where the proposed new function is clearly defined, where it allows for well-defined indicators and metrics, and crucially, adds richness to the assessment of the TIS in question, its introduction is not only justified, but necessary.

The new function proposed here is called "relative value potential" and it considers whether the technology with which the TIS is concerned has a reasonable likelihood of achieving a full niche breakout in the context of competing technologies. It explicitly forces contextualisation of the TIS model with wider factors (which would be considered regime factors within the Multi-Level Perspective framework). The interviews undertaken in this research have strongly supported the introduction of the new function proposed here.

Measures for the new function could comprise current and potential financial metrics and could also attempt to include non-financial costs and benefits. Such measures are considered further in chapter 8.

7.3 Why not include this function within another?

It might be argued that the function of relative value potential could fall within the scope of the market formation function (F5) or the legitimation function (F7).

7.3.1 Relative value potential – why isn't it contained within market formation?

In introducing a new function to the widely-used seven function architecture proposed by both Hekkert et al. [95] and Bergek et al. [92], it is important to make the case for the new function robustly.

On a first look, it might seem appropriate to embed the question of potential future value of the new technology within the function of market formation. However, a close examination of the existing definition of this function makes clear that it addresses different aspects of the TIS than the newly proposed function.

7.3.1.1 Bergek et al.'s definition

Market formation, as originally described by Bergek et al. [92], refers to development of the potential market for a technology and concentrates on the creation of the "protected spaces" in which the new technology can develop its licence to operate without concerns as to its competitiveness. In describing the creation of such protected spaces, Bergek et al. note that in the absence of this function, "market places may not exist, potential customers may not have articulated their demand, or have the capability to do so, price/performance of the new technology may be poor, and uncertainties may prevail in many dimensions. Institutional change, e.g. the formation of standards, is often a prerequisite for markets to evolve". So they noted that price/performance is a factor in the development of markets, but this is a minor element of their definition. In practice, one of the key factors of "protected spaces" is their special economic status, in which economic competitiveness is not an important factor.

Bergek et al. [92] also refer to the development of larger scale markets but focus on regulatory and societal hurdles to market formation (in their example of the Swedish mobile data services market).

This definition is "inward-looking", in that it considers the emergence of a market for the new technology, with an implied assumption that the new technology has a competitive role to play in a new stable system.

7.3.1.2 Hekkert et al.'s definition

Hekkert et al. [95] also defined a function of market formation, but they focussed exclusively on the creation of protected spaces in which emerging technologies need not be concerned with their competitiveness with incumbent technologies. Again, this was inward-looking towards the technology, and did not adequately explore the competitive world into which the new technology is emerging.

7.3.1.3 Other authors and operational practice

The review of 70 functions in chapter 4 found nine examples of functions which fell into the natural grouping called "market formation". None of these referred to the competitive potential of the emergent technology, supporting the view here that the existing definition of market formation does not address this important question.

7.3.2 Relative value potential – why isn't it contained within legitimation?

Legitimation was defined as a function in Technological Innovation Systems by Hekkert et al. [95] who described it as the "formation of advocacy coalitions". They stated that such coalitions can contribute to the delivery of the TIS: they "put a new technology on the agenda (F4 - Guidance of the Search]), lobby for resources (F6 - Resource Mobilisation) and favourable tax regimes (F5 - Market Formation)".

This definition of legitimation is focussed on the development of advocacy coalitions and the building of stakeholder and societal support for the emergent TIS, while the proposed new function of relative value potential specifically and deliberately seeks to quantitatively assess the TIS within the context of the competing technologies with which it will compete following emergence from its embryonic stages.

Accordingly, it is felt that the scope of the newly proposed function is sufficiently distinct from legitimation to warrant its separate definition.

7.3.3 Relative value potential as a new function

The proposed new function of relative value potential explicitly considers the dynamic competitive environment in which the new technology will compete. Essentially, it evaluates whether the new technology can demonstrate a pathway to viability, and it allows for viability to be defined in terms beyond the purely economic, by including societal costs and benefits and other externalities.

It is felt that the scope of the newly proposed function is sufficiently distinct from the Hekkert functions – specifically market formation and legitimation - to warrant its separate definition.

7.4 Relationships with other functions

The interviews revealed that each of the seven Hekkert functions related to the proposed new function, with the performance of each function.

7.4.1 Relationship with F1 – entrepreneurial activities

A number of interviewees alluded to the link between entrepreneurial activities and the anticipated emergence of the TIS in which those activities were taking place. This emergence, or the perception of the likelihood of the successful evolution of the TIS, requires an appreciation of the wider techno-economic context into which the TIS hopes to emerge.

WPD1 captured this by noting that entrepreneurial activities were:

> *"driven by competition, and the technology that that competition is engendering." – WPD1*

A WTG manufacturer explicitly recognised that their customers looked over an extended time horizon in considering investment, again requiring an appreciation of the techno-economic context:

> *"Our customers are very sophisticated as you'd expect them to be when they're investing in billions of pounds worth of kit. So our customers will look at the discounted cash flow impact of lifetime cost and LCOE." – WTG15*

A marine technology developer noted that:

> *"There are significant market pressures that have brought those technologies about…" – MTD22*

Again, the recognition of market pressures as a factor driving or blocking entrepreneurial activities points to the importance of the wider commercial context.

Others also pointed to the importance of competition, whether within the sector (as referenced by SO32) or from other investment opportunities within the entity considering entrepreneurial activities within the TIS (as described by SH40):

> *"So now you're seeing more competition and that also drives more and more technology competition." – SO32*

> *"So BP invested a huge amount of money in offshore wind in the early days, and had a big team looking at it, trying to understand it, but they shied away actually and I think that was probably influenced by the oil and gas price and probably uncertainty around future subsidy regimes for offshore wind." – SH40*

SH43 summed up the interaction between entrepreneurial activities and the relative value potential of a technology most succinctly:

> *"It's a chicken and egg situation. You won't have the entrepreneurs unless there's a genuine opportunity for them to exploit". – SH43*

7.4.2 Relationship with F2 – knowledge development

In the same way that entrepreneurial activities are linked to the perceived competitive potential of the TIS, so the development of knowledge (and the funding of the development of knowledge) are also influenced by the relative value potential of the technology. Cost reduction allows an emergent technology to make a case for its relative value, and knowledge development is often focussed in this area:

> *"Cost reduction continues. It has to and that's driven by competition" – WPD1*

An appreciation of the potential future market size was seen to be a powerful driver for knowledge development – and this appreciation is derived from an analysis of the potential market value:

> *"I think because of the size of the market and because of the visibility of the market going forward - the pipeline of work - I believe that in 10 years we would have moved on leaps and bounds and developed a lot more in the UK. And these could be foreign companies developing in the UK, but I'm confident that there will be a lot more engineering design development coming out of the UK - it may be foreign money that's pumped into it, perhaps with a bit of government support. But I have confidence that we will see an increase in R&D and building knowledge in offshore wind in the UK." – SC10*

> *"You need a very long term view of these things." – SC14*

The specific linkage of knowledge development to the relative value potential of the emergent technology was best described by SO60:

> *"And the I think the challenge is how do we make wind on par with other energy sources and the true innovation has been in terms of the efficiency, the cost effectiveness of it, to make sure there is parity between that and other energy source." – SO60*

7.4.3 Relationship with F3 - knowledge diffusion and networking

The diffusion of knowledge and networking are influenced by the competitive potential of the technology. As offshore wind became more competitive with other incumbent power generation technologies, competition between developers intensified and the collaborative nature of the sector changed.

SC56 felt that this should mean an increased role for collaboration facilitators, like the Offshore Renewable Energy Catapult:

> *"We have got this competitive element out there. But I think all developers of offshore wind would agree, that we've all got a common industry, we're all on the same side essentially. Offshore wind has had reasonable success*

in bringing out an industry challenge - you know - every developer faces problem A. So I think having a mechanism where we target the problems as a sector, rather than as a developer, or as a winner or a loser, that's absolutely what's required. It's back to ORE Catapults, the Offshore Wind Accelerator - I think there's a big role for these guys to possibly be a bit more powerful in terms of the knowledge diffusion." – SC56

7.4.4 Relationship with F4 – Guidance of the Search

Claire Perry, Minister of State for Energy at the Department for Business, Energy and Industrial Strategy, in her response to a query from the researcher made clear the link between F4 – Guidance of the Search and the relative value potential for emergent technologies. In her response she said that Government's policy in relation to funding took account of the potential competitiveness of the technologies seeking support:

> *"The Department is continuing to engage with wave and tidal stream developers to understand their cost-reduction trajectories, where those savings are likely to be found and,* ***importantly in light of declining costs for other renewables****, whether there may be a rationale for funding arrangements outside of the CfD." - Claire Perry, Minister of State for Energy* [154] *(author's emphasis)*

Interviewees recognised that government resources were not unlimited and that industry had a responsibility to reduce the need for ongoing support by driving costs down and removing the requirement for subsidy:

> *"General signals were that governments globally were going to be supportive of renewables* ***as long as they could show a path to being subsidy free****." – MPD24 (author's emphasis)*
>
> *"So you've got the recognition that we need to decarbonise and in some quarters it's recognised that you pretty much need to pull every lever you've got going. That's obviously got to balance with* ***giving value for money****." – SO75 (author's emphasis)*
>
> *"Having a clear line of sight to your market is super important." – SH40*
>
> *"The main driver bringing cost down is competition." - SH43*
>
> *"The development of the subsidy scheme and the clear signal that it's not going to be around forever and the competition between developers, I think, are really the important cost drivers." – WPD7*

*"Well obviously it's the economics tools, through tax incentives, it can offer support in terms of research grants, it can drive research working with the universities and the further educational institutes, it can support small companies get off the ground and get into the sector through all these various fields, it can offer support…. **But it shouldn't be doing so at the expense of other sectors which might be more commercially viable because at the end of the day, it's taxpayers' money we've got to remember.**" – PM55, (author's emphasis)*

"Primarily it comes down to cost/benefit – bang for buck in terms of taxpayers' money." – PM55

*"In 2012, we had something called the Cost Reduction Task Force that a lot of the major players participated in, which was all about meeting the government's challenge because **at the time there was a promise that government would continue to support offshore wind as long as costs continued to fall.**" – WTG12 (author's emphasis)*

"It's really important in wave and tidal. You've got a set up a clear vision about of how investment in the sector can make a return." – MTD58

7.4.5 Relationship with F5 – Market Formation

Among the interviewees, there was recognition that incentive support can only be delivered within the context of other things that government seeks to do. The importance of a financial return for investors and the government's requirement to move to subsidy-free operation over time mean that an emerging technology must be able to demonstrate a roadmap to unsubsidised operation. These thoughts were expressed by a number of interviewees:

"'Is there a demand for our product that we can deliver profitably?' And the answer to that was 'yes'." – WPD1

"The main drivers have been the support mechanisms to ensure that the developers know that they're going to get a return for their investment." – PM49

"I suppose the motivation for them to make all that investment - because you're talking hundreds of millions of pounds to develop these new turbine platforms - would have been fuelled by the availability of licensing rounds via the Crown Estate, the availability of subsidy to bring comfort that you can actually make the numbers stack up if you're a project developer." – SH40

The critical question, in the view of this research, was asked by a supply chain participant:

> *"Well, if we've got massive untapped potential on global offshore wind, why do we need...[wave and tidal]?" – SC56*

This question clearly points out the importance of the competitive potential of the new wave and tidal technologies relative to the more established offshore wind. It seems that offshore wind is on a trajectory to competing on a subsidy-free basis with other forms of electrical generation, and there are many potential development sites offering grid-scale potential. In this context, it appears to be a legitimate question as to why incentives and financial support for tidal stream and wave should continue to be made available.

7.4.6 Relationship with F6 – Resource Mobilisation

Resource mobilisation is closely related to the commercial potential of the emerging technology, as the decision by developers, supply chain and financiers to allocate resources will be determined by the competitive prospects of the emerging technology.

This requires a degree of perspective:

> *"You need a very long term view of these things." – SC14*

It also requires a recognition that investors and participants need a return on their investment:

> *"In terms of a return, in terms of a regular opportunity to bid in, in terms of the amount of capacity that would be produced, in terms of the price that they would receive for that power." – PM30*

The emerging TIS competes with incumbent technologies, and has to offer returns commensurate with the risk:

> *"I think oil and gas companies are getting more interested in it. It must be tough for them because they are used to very high returns and they obviously see them out there." – SO32*

7.4.7 Relationship with F7 - Legitimation

The legitimacy of offshore wind and marine technologies is strongly driven by its perceived potential to operate without subsidy. A technology with a clear pathway to subsidy-free operation will generally find it easier to attract public support than one needing special support.

This legitimacy contributes to what Geels [82] would describe as “landscape” factors, such as the general societal stance towards climate change and renewables, and “regime” factors, such as the cost of alternatives, including nuclear and onshore wind, the impact of carbon costs and other potential climate change measures:

> *“But of course the whole energy system has to fundamentally shift. So, I think this is a transition for society and society will get there because actually this is about potential for extreme weather and other elements.” – SO60*

> *“So on one on one side I can see that it's driving towards the government's requirement to decarbonise at lowest cost. But I find it difficult to reconcile that against nuclear, for instance, where we've decided we're going to pay £90/MWh for 40 years and that was a government decision.” - WPD63*

> *“The only anti argument at the moment really is the cost of electricity. There are definitely people making politics out of saying ‘well that the cost is going up because of all this investment in renewables’, and we shouldn't be investing in renewables, we should be pulling the cost of electricity down and UK electricity is more expensive than the rest of Europe and all kind of stuff. And a lot of that is misinformation…and I think that the challenge on acceptance is down to the cost of electricity.” -SC14*

> *“Is Hinkley Point C a good investment of taxpayers' money? No, I don't think it probably is. Is investing in future nuclear part of the future energy mix? Yes. Should it be commercially viable, like we're saying everything else can be? Yes.” – PM55*

> *“I think - the challenges that we see with onshore wind, in terms of its acceptance, are benefiting offshore wind.” - SO32*

Consideration of the value (whether actual or potential) can be widened to include factors beyond the direct financial comparison, including, for example, the creation of jobs and export industries:

> *“The idea that renewables was the big first bold step that the UK could make into its national contribution to climate change and that we were going to grab this new industry and make it a UK one.” - PM30*

7.4.8 Relationships with other functions - conclusion

Table 7-2 summarises how relative value potential can impact each of the seven Hekkert functions, with specific examples from the offshore wind/marine renewables interaction.

Relationship between relative value potential and Hekkert function	General impact	Specific example
F1 – Entrepreneurial activity	Entrepreneurs motivated by potential for profit, so changes to context impact population of motivated entrepreneurs	Inventors and entrepreneurs in marine engineering now more likely to focus on offshore wind supply chain rather than device development. For example, Engineering Business/OSBIT has evolved from developing a tidal stream technology to developing access systems for offshore wind
F2 – Knowledge development	Public and private funding for research guided by perceived market opportunity; changes to techno-economic context impact or drive research funding	Private funding for technology development in marine renewables has become very difficult, as market perception of potential value is poor. Interviews confirmed marine "over-promising" has damaged perceptions of the sector
F3 – Knowledge diffusion and networking	Networks may wither if techno-economic context degrades, although little evidence of this	Offshore wind networks are strong; marine networks engaging with changing techno-economic context to recast marine benefits as societal rather than purely financial
F4 – Guidance of the Search	Policy co-evolves with technological viability; changes to techno-economic context influence policy direction	Policy has strongly co-evolved with offshore wind, to ensure an appropriate level of funding to maintain development and deployment; marine support now hard to access as viability of the sector is in doubt. CfD scheme unambiguously aimed at offshore wind, but very hard for marine to access
F5 – Market formation	Creation of "protected spaces" is only justifiable if roadmap to viability is clear; techno-economic	Change from banded RO to CfD has shifted focus of financial support to "winning" offshore wind technology and removed higher support levels for tidal or wave

	context defines the roadmap	
F6 – Resource mobilisation	Businesses will only allocate resources in response to clear market opportunity; techno-economic context defines that opportunity	Major investments being directed into offshore wind, but significant players withdrawing from marine in response to techno-economic context. For example, SSE has withdrawn from wave, Siemens, Rolls-Royce, Naval Energies and General Electric have all withdrawn from tidal in recent years
F7 - Legitimacy	Legitimacy strongly impacted by roadmap to viability, as accusations of wasting money (especially government money) are very damaging	Offshore wind clearly vindicated as part of the future as demonstrated by the "Sector Deal", but marine sector having to redefine its value to maintain legitimacy

Table 7-2: Relationships between Hekkert functions and "techno-economic context" (author's analysis)

7.5 Further aspects of relative value potential

7.5.1 Actors

The actors involved in the functional activities identified in the foregoing Sections 6.2 and 7.4 are the same as those in the seven Hekkert functions as discussed in chapter 4. The additional perspective introduced by this analysis is that it requires the actors to maintain an awareness of each other's activities and understand how those actions may impact their own development.

Type of actor	Typical activities	Wind vs Tidal Stream and Wave
Government and Policy maker	Determine policy and co-evolve policy with technology development, allocating funding support in response to technology development	Offshore wind recognised to offer commercially-viable potential at scale, wave and tidal still uneconomic and small scale
Technology developer	Development of technology, develop and maintain competitive positioning, lobby for funding support	Wind turbine manufacturers now fully commercial, with main dimension of competition being turbine capacity; marine developers focussed on technology development and making case for funding
Project developer	Development of projects in the context of policy and funding support	Project funding options clear and robust for offshore wind; financial returns for marine not clear (in UK)
Supply chain	Provide goods and services as contracted	Supply chain operates wherever technology and project originators have a requirement and funding
Support organisation	Inform and influence policy makers, create networks among technology and project developers	Support organisations active in both sectors
Stakeholder	Observe, commentate, input to policy, technology and project development depending on stakeholder goals	Active in both sectors, depending on stakeholder goals
Investors	Provide funding, with investor type driven by risk and return profile of investment	Offshore wind risk/return profile maturing such that insurance companies/pension funds and other long term infrastructure funds are investing; marine still very high risk, appealing to venture capital

Table 7-3: Actors involved(Author's analysis)

7.5.2 Institutions

In all of the functional definitions, differentiating between networks and hard institutions can be difficult. This is equally true in this new proposed function.

"Hard institutions"

Many of the hard institutions involved in the functional activities described in this chapter have been described in chapter 5. However, in relation to the activities described here, the critical difference is that the relevant hard institutions are those which "look beyond" the technologies in the TIS and consider the wider competitive framework.

The hard institutions identified in this chapter define the competitive setting. They therefore include the financial support arrangements which directly impact offshore wind and marine renewables, such as the Renewables Obligation and Contracts for Difference. Unlike any of the other functions, the hard institutions affecting the competitive context also include those which affect the financial returns of competing sectors, such as carbon pricing affecting the comparative economics of coal and gas fired generation.

Other relevant hard institutions include the laws and regulations affecting the technologies in the TIS, together with planning, licensing and permitting schemes.

As Section 6.2 shows, hard institutions governing the non-financial benefits of the technologies also bear on this competitive positioning. For example, laws which specify non-polluting electricity generation, or regulatory systems which encourage or limit offshore wind relative to marine are all hard institutions with an impact on competitive context.

"Soft institutions"

Soft institutions for this function, like its hard institutions, include those soft institutions with affect the competitive viability of offshore wind and marine relative to electricity generation alternatives.

These include social attitudes to pollution and climate change, which provide the social licence to operate for renewables (or remove the social licence to operate for coal, gas or nuclear). Social attitudes towards the acceptability of renewables, including the relative attractiveness of offshore wind or marine relative to onshore wind (as explored in Section 5.8) are also relevant.

Trends in investment are another soft institution bearing on competitive positioning for the emergent technologies. Venture capital investment is susceptible to trends – in the early years of the 21st century, venture capital took a keen interest in wave and tidal technologies, potential in response to aggressive pitches by device developers, as discussed by one of the support organisation interviewees:

> *"With wave and tidal, I think what's happened is the industry have had to be fairly bullish to secure their investments from...certainly from the private sector, they've had to promise a lot." – SH40*

The same interviewee went on to describe the result for investors, which resulted in their withdrawal from the sector, as other sectors offered apparently more attractive returns:

> *"And generally they underdelivered on those promises, because actually it was a pretty tough gig." – SH40*
>
> *"Because the wave and tidal developers had made those promises to the private sector, they [government] then used the same set of policies to agree a policy framework to deliver wave and tidal…so they then rushed to the first farm stage and had a nightmare, as was to be expected." – SH40*

One marine technology developer explained how investors had achieved little through their investment in the marine sector leading to their withdrawal:

> *"In our time in the sector, the only thing shareholders had to show for their investment was the knowledge and the Intellectual Property that had been gained and that we had created." - MTD58*

The soft institutions impacting the competitive positioning of an emerging technology operate in the wider business and social environment, and crucially include institutions which look outside the factors directly affecting the technologies in the TIS to other technologies with which the TIS technologies compete.

7.5.3 Networks

As with the list of actors, the networks relating to these functional activities are the same as those identified for the seven Hekkert functions. In addition to the roles played by networks in the seven Hekkert functions, they provide one of the means by which actors can share information about their competitive positioning.

The networks with a particular bearing on the new function are those which enable actors in the sectors to understand how the competitive environment is evolving. These include the trade associations (e.g. RenewableUK, Scottish Renewables), test centres and their clients (e.g. European Marine Energy Centre, WaveHub, Offshore Renewable Energy Catapult's wind energy test facilities at Blyth) and collaborative programmes (e.g. the Carbon Trust's Offshore Wind Accelerator).

These networks play a crucial role in informing actors of the state of development of their sector, and their rivals within it, as well as maintaining a watching brief over the broader commercial environment.

7.5.4 Metrics, indicators and drivers

This section reviews the interviews to glean insights on potential measures for the function.

The first priority for interviewees in metrics was financial, as discussed in section 6.2.1 and in additional remarks:

> *"How should governments - and it doesn't need to be government - how should anybody assess that question, do you think, of that economic potential? The value test if you like." - PM55*

> *"They [technology and project developers] are doing it to bring down their future costs or to increase their future revenue." – PM49*

The dominant economic metric was levelised cost of energy:

> *"Our Customers are very sophisticated as you'd expect them to be. When they're investing in billions of pounds worth of kit. So our customers will look at the discounted cash flow impact of lifetime cost and LCOE." - WTG15*

> *"And one of the key pieces work we do is analyze their cost of energy predictions and forecasts. So we've run a levelized cost of energy baseline model that's populated with data around cost of steel, the cost of vessels, performance factors and things like that. So we'll try and benchmark a technology, to run a cost of energy model." - SO77*

The wider social benefits of renewable technologies were also considered, with interviewees proposing a number of potential dimensions on which social benefits might be assessed.

> *"Right from the time that you produce it, to the time that you consume it. And the results of producing and consuming it are such that you produce or you have a carbon cost - is the easy way of putting it. And if you start to roll in things like health effects into that carbon cost, such as, let's say, I don't know, in central London how many people die of respiratory failure as a result of the vehicles that are burning the carbon fuel etc." MTD22*

Finally, technological assessment measures were proposed, with multiple interviewees using the Technology Readiness Level (TRL) concept as a shorthand for technical development:

> *"I can't really say in all honesty that every single device that went into the water was at the right TRL level to do so." - PM65*

"So research has been a big thing and remains a big thing and you know look at the technology journey a lot of that is driven by the OEMs but also a lot is coming out for early TRL and mid TRL investments. I would maybe point to the offshore wind accelerator where the siting of offshore wind turbines in an array has benefited from that sort of mid TRL collaborative research." - WPD1

These suggestions of potential dimensions of assessment are considered in further detail in Chapter 8.

7.5.5 Validity

The review of the interviews found strong support for a new function which addresses the potential value of emerging technologies in the context of their competition. There was wide acceptance of the importance of an emerging technology maintaining a competitive position relative to both incumbent technologies and competing emerging technologies.

Comments addressed the need for competitive cost of energy:

"Showing material progress in cost of energy, which of course is critical for the sector." – MTD58

Other comments emphasised that the roadmap to competitiveness was critical:

"It's super important. Having a - whatever stage you're at in terms of technology - having a clear line of sight to your market is super- important." – SH40

This roadmap was seen as a critical motivating factor, for investors, for project developers, and entrepreneurs, as indicated by a stakeholder:

"You won't have the entrepreneurs unless there's a genuine opportunity for them to exploit." – SH43

When a new function to address these competitive factors suggested, interviewees' views were well summarised by one of the policy makers:

"I agree that's really important." – PM29

Full validation of the proposed new function requires additional research. Extending the research approach used in this work, in which interviewees' qualitative and quantitative evaluation of the full list of functions, to include the proposed new function, might be revealing in this regard.

7.6 Relative Value Potential – Conclusions

Analysis of the interview data supported the hypothesis that the seven Hekkert functions did not form a "necessary and sufficient" framework for describing the emergence of a new technology. While the seven Hekkert functions were widely agreed to be necessary, and the scoring in Sections 5.2.4 to 5.8.4 confirms this, there was wide agreement that they were insufficient, as they did not adequately take account of the wider techno-economic context into which the new technology aimed to emerge and its relative value potential.

Further, analysis of the interview data found that a coherent set of comments suggested that an additional function was required to explain the emergence of offshore wind, and the relative failure of tidal stream and wave energy to achieve a similar niche breakout. The case for the proposed new function of relative value potential is set out in Section 7.1 and tested in Sections 7.2 and 7.3.

This chapter has defined that function as "relative value potential" and explored whether it should be subsumed into a function within the existing functions inventory. It concludes that it should be defined as a separate function, and considers the relationship between this new function and the pre-existing seven functions in Section 7.4.

The chapter goes on to describe the new function according to the same structure as used for the seven Hekkert functions (see chapter 5): the actors, institutions and networks relating to this new function are described and interviewee comments on potential metrics, indicators and drivers are summarised. Finally, the validity of the function, as expressed by interviewee comments, is reviewed in Section 7.5.

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8 Evaluating relative value potential

Chapter 7 defined the new function and Section 7.5 described some interviewees' thoughts on potential measures.

This chapter expands on that section by considering and testing a number of potential measures (comprising metrics and indicators). It begins by briefly revisiting the literature on metrics, drivers and indicators, before considering technical measures, where Technology Readiness Levels are well established as a framework within which to assess the technical viability of an emerging technology.

The chapter moves on to consider economic measures which would allow the comparative evaluation of alternative technologies including externalities.

Finally, noting that data is not available to meaningfully assess wave and tidal technologies, it seeks to apply these measures to compare the relative value potential of offshore wind against a counterfactual of Combined Cycle Gas Turbines (CCGT), using both quantitative measures (where possible) and qualitative evaluations where quantitative measurement is not possible. CCGT is selected as the counterfactual, as it is currently the largest contributor to UK generation at present (see Figure 1-1)

8.1 Drivers, indicators and metrics

As discussed in Section 2.3.4, the literature refers to metrics, indicators and drivers, where metrics are quantitative measures of functional performance, while indicators are more qualitative demonstrations of support for the emerging TIS [96]. In other terms, metrics can be described as things that can be directly measured, while indicators are descriptions of areas in which metrics might be developed [97] and drivers are very similar to functions as processes which require to be measured.

8.1.1 Drivers

As Darmani et al. describe them, drivers are "factors that foster RETs (Renewable Energy Technologies)…defined as 'the processes that influence trends and our ability to meet agreed-upon targets.'" The description of drivers as "processes" establishes some dimensions along which indicators and metrics can be developed.

Commonly mentioned drivers, as Darmani et al. suggest, include

- energy related policy
- firms' pioneering activities
- market demands and feedbacks
- society awareness and preferences
- technological development and knowledge breakthrough

As these drivers are effectively contained within the Hekkert functions (see Table 8-1), this research does not employ them further, but notes that the driver of "market demands and feedbacks" not only maps into Hekkert's F5 – Market Formation, but also contains the notion of relative value potential in its description of market feedbacks.

Darmani driver	Hekkert function(s)	Comments
Energy related policy	F4 – Guidance of the Search	
Firms' pioneering activities	F1 – Entrepreneurial Activities and F6 – Resource Mobilization	
Market demands and feedbacks	F5 – Market Formation	Also contains relative value potential, as captured in market feedback
Society awareness and preferences	F7 - Legitimation	Some role for relative value potential, as emerging technology can offer societal benefits relative to incumbent technologies
Technological development and knowledge breakthrough	F2 – Knowledge Development and F3 – Knowledge Diffusion and Networking	

Table 8-1: Mapping drivers to functions (author's analysis)

In moving through the hierarchy of specificity of drivers, indicators and metrics, the analysis of the interviews strongly suggests that the more specific indicators and metrics should consider not only the technical viability of the emergent technology, but also its potential for economically competing with incumbent technologies, including the other benefits which the emergent technology might offer, thereby contributing to its relative legitimacy.

8.1.2 Indicators and metrics

Indicators and metrics are required to allow a quantitative comparison of the economic and other performance of the TIS technology with the technologies with which is aiming to compete. In addition, where the TIS technology is not proven, a clear roadmap to techno-economic delivery is required and this requires a framework for techno-economic assessment of the TIS technology and its potential.

This section draws on relevant literature and the interviews to develop a range of potential measures for the newly proposed function of techno-economic context.

As previously set out, technological viability is the first area in which techno-economic context indicators and drivers are defined, followed by economic measures and assessments of other benefits.

8.2 Technological viability

The first step in evaluating the techno-economic context function is to assess the technological roadmap for an emerging technology. Such a roadmap can provide insight into how a technology of interest may progress from being conceptual, to prototypical and ultimately to commercially deployable.

Early thinking in the area of energy innovation systems identified sequential phases of development which were commonly characterised as basic R&D, technology R&D, market demonstration, commercialisation, market accumulation and diffusion [166]. This was later made more memorable as "research, development, demonstration, market formation (or deployment), diffusion" [167].

It is important to note that later work recognised that this model was overly simplistic [96], as it did not take account of feedbacks between developmental stages, and between the market (and competing technologies) and the emergent technology of interest. In time, this lead to the development of the concept of Technological Innovation Systems, as described in Chapter 2.

That said, the availability of simple measures to assess the stage of technology development remains a critical element of the assessment of technological maturity. The leading measure – the Technology Readiness Level (TRL) – was defined by NASA's John Mankins [168] as "a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology". TRLs have now been widely adopted (e.g. EMEC [169]) and are used across many industries.

In summary, the TRL scheme defines nine levels, as summarised below:

Technology Readiness Level	Criteria
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of- concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight proven" through successful mission operations

Table 8-2: Technology Readiness Levels, from [168]

These have been modified and adapted for various purposes since their original specification. For example, EMEC has developed a tailored version for wave and tidal devices [169]), as shown in Table 8-3.

As offshore wind and its counterfactual of CCGT generation have clearly achieved TRL 9, this research does not further investigate Technology Readiness Levels.

Wave energy development protocol		Tidal current development protocol
Stage 1 **TRL 1-3**	Concept validation. Prove the basic concept from wave flume tests in small scale	Tidal-current energy conversion concept formulated
Stage 2 **TRL 4**	Design validation. Subsystem testing at intermediate scale, Flume tests scale 1:10, Survivability; Computational Fluid Dynamics; Finite Element Analysis Dynamic Analysis; Engineering Design (Prototype); feasibility and costing	Intermediate scale subsystem testing, Computational Fluid Dynamics, Finite Element Analysis, Dynamic Analysis
Stage 3 **TRL 5-6**	Testing operational scaled models at sea + subsystem testing at large scale	Subsystem testing at large scale
Stage 5 **TRL 9**	Economic validation; several units of pre-commercial machines tested at sea for an extended period of time.	Commercial demonstrator tested at sea for an extended period.
Stage 4 **TRL 7-8**	Full-scale prototype tested at sea	Full-scale prototype tested at sea
Stage 5 **TRL 9**	Economic validation; several units of pre-commercial machines tested at sea for an extended period of time.	Commercial demonstrator tested at sea for an extended period.

Table 8-3: EMEC TRL definitions; source [169]*)*

8.3 Potential economic metrics

Once an emerging technology reaches TRL 9, it has demonstrated its technical viability. At this stage, its acceptance is largely determined by its cost of energy – an economic measure. Conventionally, the economic performance of energy generation alternatives, such as offshore wind, is measured in terms of cost per unit energy delivered, although there is considerable discussion about the merits of such measures [170]. While it is accepted that these measures have weaknesses (as described by, for example, [171]), they are well established and widely used.

8.3.1 Cost per unit energy measures

Aldersey-Williams and Rubert [172] reviewed a wide range of unit cost of energy measures, including undiscounted cost of energy and alternative definitions of discounted cost of energy. They concluded that Levelised Cost of Energy, as defined by the UK Government's Department for Business, Energy and Industrial Strategy, is a preferred measure to apply, and found that the strengths of $LCOE_{BEIS}$, as they term it, include "simplicity, sophistication, interpretation and adoption".

8.3.1.1 Levelised Cost of Energy

As Aldersey-Williams and Rubert [172] explain at some length, the Levelised Cost of Energy describes the unit cost of energy, including the financial return on the investment required to fund the plant. It is defined by Equation 1:

$$LCOE_{BEIS} = \frac{NPV_{Costs}}{NPE} = \sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t} \Bigg/ \sum_{t=1}^{n} \frac{E_t}{(1+d)^t} \qquad (1)$$

where t is the period ranging from year 1 to year n, C_t is the capital cost in period t (including decommissioning), O_t is the fixed operating cost in period t, V_t is the variable operating cost in period t (including fuel cost, carbon costs, and sometimes taxes, etc.), E_t is the energy generated in period t, d is the discount rate, and n the final year of operation [172].

Aldersey-Williams and Rubert (2019) describe the four strengths of $LCOE_{BEIS}$ as follows:

- Simplicity: the formula is clearly and easily defined and evaluated, and reduces complex comparisons to a single number
- Sophistication: the formula takes account of life time costs and energy production, including the cost of capital
- Interpretation: the formula returns a value equal to the constant real terms price needed per unit energy to return the rate of return implied by the discount rate

- Adoption: the formula is already widely used

For these reasons, it makes sense to continue to use this definition, extended as appropriate to account for externalities (see Section 8.4), as a comparative measure.

8.3.2 Learning and experience curves

LCOE is a snapshot of unit cost of energy at a particular stage of development. In an evolving setting, it is also important to be able to develop a "roadmap" of technological development, to show how an emerging technology can develop its competitive positioning.

The concept of a learning curve (also known as an experience curve) was first introduced by Wright [173] in his important paper "Factors affecting the Cost of Airplanes". He found that there was a relationship between the cumulative production of a model of an aeroplane and its unit cost, in which the cost fell in line with the logarithm of the total number of units produced.

These ideas have been the nucleus for a huge literature, in which researchers have sought to find similar patterns in other areas and to account for more complex patterns. For example, van der Zwaan [174] suggested normalising unit costs to take account of the exogenous variability of certain significant costs (in his case, copper costs in wind turbines) and Ferioli [175] who sought to disaggregate total costs to model costs with different learning characteristics differently.

It is beyond the scope of this research to explore the application and relevance of learning curves to offshore wind, tidal stream and wave energy in detail, but it is clear that the potential for cost reduction is an important aspect of the relative value potential for an emerging technology. Those technologies with more potential for rapid cost reduction (or greater cost reduction for the same aggregated installed capacity) clearly have more competitive potential than others with less cost reduction potential.

Although the scope of this work precludes an in-depth consideration of learning curve ideas, it is important to note that Wright's original work related to mass production of the same model of aircraft, so that manufacturing experience or "learning-by-doing" would apply to all future production. As interviewee SH40 noted, the lack of convergence in tidal stream technologies, and especially in wave energy devices, will have an effect on the achievable learning rates and cost reduction potential. They pointed to Nova Innovation, whose smaller scale devices allow for more rapid doubling of installed base relative to Atlantis, whose devices are larger[13]:

So I have a lot of sympathy for Nova's approach. Their doubling rate - so say we just select Nova as the winning technology and we say we still want to get to 300 MW, they would deploy 3000 devices by that point yet and Atlantis would have only deployed 300. So in terms in terms of the progress rate they're making, Nova are learning ten times faster than anyone else for a given deployment rate." - SH40 (learning rate)

That said, learning curves and the implied expectation of reduced unit costs form a critical part of the case that the ORE Catapult sought to make in its report [176] in relation to the potential emergence of tidal stream, and in the longer term, wave energy.

Similarly, learning effects are expected in offshore wind cost trends. Lindman and Soderholm [177] undertook a meta-analysis of learning rates in onshore wind (there was, and is currently, insufficient information for a similar assessment in offshore wind). They found that an approximate learning rate for onshore wind was 10% per doubling in installed capacity.

8.4 Incorporating externalities – Full Cost of Energy

The economic discussion in Section 8.3 has focussed on the costs and energy directly attributable to the generation technology at the point of delivery to the National Grid. However, a full evaluation of the costs and benefits of technology alternatives must use a wider lens, taking account of the effects on the National

[13] Nova Innovation is, at the time of writing, focusing on array-scale deployment of 100 kW devices, while Atlantis is deploying 1.5 MW scale devices.

Grid of technology choices, and assessing the costs and benefits lying beyond the scope of a technology-focussed LCOE evaluation.

As discussed, LCOE evaluates the direct costs of electricity generation alternatives, and in this definition, includes costs up to the point of connection to the National Grid. The energy transition will also involve costs for re-configuring the National Grid to accommodate electricity generated by renewable sources which are generally located far from demand, geographically dispersed and produce intermittent output. These costs may include the development of storage solutions to manage intermittency from renewables, as well as other grid reinforcing measures. Evaluation of their scope is beyond the remit of this research, although it is noted that in the case of any marginal addition to generation, these costs may be disregarded.

The costs and benefits of offshore wind, and in the longer term tidal stream and wave energy, are not limited to the purely economic costs endogenous to the devices and projects being deployed. As with all economic activity, they also involve costs and benefits which are not captured by the limited LCOE metric described above. These external costs and benefits are known as "externalities" [178].

As the Stern report [179] pointed out, "the climate is a public good…markets do not automatically provide the right type and quantity of public goods…thus, climate change is an example of market failure involving externalities and public goods." This section is concerned with identifying a range of externalities relevant to a full appraisal of the techno-economic context of offshore wind, tidal stream and wave energy. While these include the very large scale (and hard to evaluate) externality benefits of displacing fossil fuel generated power, they also extend to smaller scale costs and benefits.

The section leads to the proposal of a new metric: Full Cost of Energy, which adds a term to the earlier definition of LCOE, from Aldersey-Williams and Rubert [172], as shown in Equation 2:

$$FCOE = \frac{NPV_{Costs} + NPV_{Externalities}}{NPE} = \left. \sum_{t=1}^{n} \frac{C_t + O_t + V_t + Ex_t}{(1+d)^t} \right/ \sum_{t=1}^{n} \frac{E_t}{(1+d)^t} \qquad (2)$$

where the new term, Ex_t, is the externality cost in period t.

This equation allows for the incorporation of contextual effects, in the shape of externalities, and can therefore be best used to compare alternative technologies, rather than being used for a single technology in isolation to attempt to derive a minimum price an investment project might require.

Care must be taken to attribute externalities to the technology to which they relate. For example, in comparing fossil-fired power generation with wind power, it is important that the external cost of, for example, air pollution, be attributed as part of the fossil FCOE rather than as a benefit in the FCOE of offshore wind. This is because the benefit offered by offshore wind in this area is only capable of evaluation in the context of the energy mix being displaced.

Externalities arising from the deployment of a technology may be positive or negative. A positive example might be the creation of a local community fund funded from the revenues of a wind farm, while a negative example from the same technology might be the visual impact on the amenity value of an area.

8.4.1 Additional externalities identified in research

Externalities have provided a rich area of research and this section seeks to develop a comprehensive (although inevitably not complete) list of externalities by reviewing the literature and analysing the research interviews undertaken as part of this study.

Table 8-4 sets out this list, organised according to the "PESTLE" mnemonic, noting that some externalities could be categorised in more than one of the PESTLE categories. The PESTLE mnemonic summarises "Political", "Economic", "Social", "Technology", "Legal" and "Environmental" [180]. It is clear that the full range of externalities can be lengthy and wide-ranging – in practice it may well only be limited by the time available to generate and capture new ideas.

The majority of the focus in the literature on renewables externalities is on environmental externalities. Pearce et al., in their seminal "Blueprint for a Green Economy" [181], split these into two value types: "user value" and "intrinsic value".

- User value: the value derived from use of the environment, comprising the actual use value. In the case of thermal power generation, this relates to the use of the environment as the waste disposal sink for waste products, and the value attached to that use. This includes option value: the value of the potential to exploit the environment;

- Intrinsic value: the value of simply knowing that that aspect of the environment exists. The example Pearce et al. give is the existence of whales – they suggest that this has a value, even though those attributing that value have no expectation of ever seeing one. An extension might be to include within intrinsic value the unknown impacts the extinction of that environmental factor might involve. Current concerns on bee extinction are an example here. There has been considerable press coverage recently on the potential impact on human food supply of bee extinction [182]; it might be argued that the intrinsic value of bees is far in excess of the value which the general public might attach to their presence.

Externality	**Source**	**Category (PESTLE)**
Fuel independence	[183]	P
No fossil fuel needed	[183]	P
Independence from oil/security of energy supply	[183] / Research interviews	P
Coherent environmental policy	[183]	P
Reduced number of blackouts	[183]	P
Building awareness of environmental and climate change issues	Research interviews	P
Motivating the public to modify their energy behaviours	Research interviews	P
A feeling of involvement in electricity generation	Research interviews	P
Support for political parties with whom voters agree on electricity policy	Research interviews	P
Royalty fund for green purposes	[183]	Ec

Job creation	[184] / [45]	Ec
GVA	[184] / [45]	Ec
Export potential and future market value	Research interviews	Ec
Transfer of some electricity revenue to local community earmarked for nature conservation	[183]	S
Type of ownership	[183]	S
Stakeholder consultation	[183]	S
Recreational activities associated with an artificial reef	[183]	S
Changing social attitudes to renewables	Research interviews	S
Increased social cohesion in communities benefiting from renewables projects	Research interviews	S
Technological improvements in oil & gas from offshore wind, tidal stream, wave	Research interviews	T
Increased development of battery technology in response to market demand from renewables	Research interviews	T
Adoption of contractual structures and commercial terms from offshore wind into oil & gas	Research interviews	L
New legal precedents	Research interviews	L
Avoiding emissions in general	[183]	Env
Avoiding greenhouse gas emissions	[183] / [185]	Env
Improvement of air quality (impacts on visibility, acid rain, respiratory problems)	[183] / [186] / [187]	Env
Avoiding environmental drawbacks of coal	[183]	Env
No water used	[183]	Env
Biodiversity	[183]	Env
Effects on biodiversity	[183]	Env
Effects on habitat and flora	[183]	Env
Effects of fauna and bird life	[183]	Env
Visual impacts	[183]	Env
Terrestrial visual impacts	[183] / [185]	Env
Marine/coastal visual impacts	[183] / [188] / [189]	Env
Visual impacts associated with residential proximity	[183] / [185] / [188] / [189]	Env
Noise impacts	[183] / [185]	Env
Green policy	[183]	Env
Location	[183]	Env
Land area effects	[183] / [185]	Env

Table 8-4: List of externalities (author's analysis)

8.4.2 Evaluation of externalities

A number of authors have considered the question of valuation of externalities in the electricity sector; some of the key contributions are summarised below.

In evaluating externalities it is critical to attribute the external benefits and disbenefits to the technology which causes them, and therefore the counterfactual technology must also be defined and assessed. It is easy to see why: if a wind farm is an alternative to coal-fired generation, its relative value is higher (in terms of pollutants avoided) than if it replaces nuclear. and the pollution benefit attached to the choice of wind over the alternative can only be calculated as part of the total cost of the alternative technology, rather than the wind farm.

In early work in the area, Pearce et al. [181] set out principles of evaluation for externalities and described some valuation methodologies but did not attempt specific application.

Roth and Ambs [187] presented a full cost approach to incorporating externalities in LCOE calculations. They defined LCOE on an annual basis (the same as the definition of $LCOE_{NREL}$ from Aldersey-Williams and Rubert [172]) in which they added the estimate of external costs for each year to the LCOE to derive a full cost of energy estimate. They included externalities including "damage from air pollution, energy security, transmission and distributions costs and other environmental impacts" [187] and applied a "control cost" methodology to estimating environmental costs for atmospheric pollutants. Under a control cost approach, the cost for each pollutant is determined by considering the cost required to be incurred to "control or clean up emissions".

Roth and Ambs took the view that these are a reasonable approximation of the cost of the environmental damage and found that the total externality costs of CCCGT amounted to $73.1/MWh while utility scale wind turbines externalities amounted to $21.3/MWh.

An alternative approach would be to use estimates of the actual damage incurred (so-called "damage costing") [190]. Damage costing-based estimates are considered to be more useful, as control costs are not in fact imposed on generators (even if they are considerably lower than damage costs) so, in the absence of mitigation, the damage is actually incurred, and the damage costs provide a better estimate of the externality's impact. That said, Roth and Ambs' estimates provide a useful cross check for the magnitude of the costs assessed in this work.

Moran and Sherrington [185] undertook a comparative economic assessment of gas-fired and wind-based electricity generation for a particular onshore site and accounted for externalities, including carbon dioxide emissions, visual and noise disamenity. While they demonstrated a practical application of the Willingness to Pay valuation methodology[14], they did not consider or evaluate the differential health effects from the generation alternatives. In addition, since their assessment related to an onshore site, its assessment of visual (and other) disamenity is not relevant to this discussion, and it is not considered further.

Krueger et al. [189] also applied an implied willingness to pay approach to assessing the visual disamenity impact of an offshore wind farm in Delaware, and demonstrated the cost of applying this method, as they surveyed several thousand households. They found that at distances offshore in excess of 6 miles, the negative externality relating to visual disamenity was negligible. As most UK offshore wind farms are (and will be) more than 6 miles offshore, a figure of zero can reasonably be taken for this negative externality.

Ladenburg and Lutzeyer [188] undertook a focused meta-analysis of earlier work on visual disamenity for offshore wind. The studies on which they based their work (which included Krueger's) relied on Choice Experiments ("CE") and explored the specific effect on visual disamenity of distance from shore. Ladenburg and Lutzeyer also described the Contingent Valuation Method ("CVM"), under which respondents are asked to evaluate specific hypothetical scenarios, by evaluating their "Willingness to Pay" or "Willingness to Accept" [190] to generate a perceived value for a non-market good. They confirmed Kreuger's findings that as the

[14] Willingness to Pay values externalities by asking potentially affected stakeholders how much they would be willing to pay for a benefit or to avoid a disbenefit

distance offshore increased, the visual disamenity reduced, but their analysis is not readily interpreted in terms of FCOE. Accordingly, Kreuger's result is used here.

Millstein et al. [186] recognised that the contributions to airborne pollution of conventional thermal generation had a quantifiable effect in terms of health effects. They went on to evaluate the health impact cost, in terms of mortality and morbidity, from this pollution. A final step, that they did not take, was to convert these cost impacts into a direct cost per MWh for conventional generation. This extra step is taken in this research in Section 8.5.3.1.

Crooks et al. [184] evaluated the job creation/Gross Value Added externality by applying a "Socio-economic Cost of Energy (SCOE)" approach, in this case in a wave energy converter project. This ties in well with the recent suggestion by consultants BVG [45] for consideration of local content and GVA to be considered in evaluating electricity generation alternatives. As this research is focussed on the relative FCOE of offshore wind and CCGT, this result is not directly relevant, although the existence of the methodology presents an opportunity for further work.

Finally, Mattman et al. [183] undertook a wide ranging meta-analysis of the externalities of wind power, which found that the literature had identified a wide range of externalities. They grouped these under the headings of air pollution and climate change, fuel independence, biodiversity, visual impacts, noise impacts, green policy and other (comprising location, type of ownership, stakeholder consultation, reduced number of blackouts, land area affected and recreational activities associated with an artificial reef).

In their review, Mattman et al. included the avoided disbenefits from the conventional power generation as a positive externality (i.e. value) of wind power. It would be more correct to include the actual disbenefits as a cost of conventional generation in a system-wide review, when comparing conventional and renewable alternatives (as Moran and Sherrrington did), as the exact mix of conventional generation displaced by any wind project, and therefore the disbenefits avoided in terms of carbon emissions, pollution etc., is specifically determined by the specific circumstances. Put another way, the negative externalities should be calculated as part of the counterfactual case, rather than attempting to include them in the main evaluation. It is easy to see why: if a wind farm is an alternative to coal-fired generation, its relative value is higher (in terms of pollutants avoided) than if it replaces (say) nuclear, or older wind. Therefore the pollution benefit attached to the choice of wind over the alternative can only be calculated as part of the total cost of the alternative technology, rather than the wind farm.

The literature describes a number of approaches to valuing externalities: these are tabulated in Table 8-5 [181,183-185,189].

Name	Methodology	Suitable for
Direct estimation / Damage cost	Estimated from measures of known impacts	Pollution and waste products, health impacts. Value limited to known impacts
Control cost	Value estimated with reference to costs required to control or mitigate impact	Pollution and waste products. Limited as only accounts for known costs of control/mitigation and can not include unknown impacts
Willingness to accept / willingness to pay	Affected stakeholders (or sample of them) asked what payment they would require to compensate for perceived impact or what they would pay to avoid perceived impact	All factors
Choice experiments	Aims to explore alternatives with equivalent utility, to "convert" unquantified into quantified assessments	Applicable for factors where direct estimation and control costing not available
Surrogate market	Value with reference to appropriate surrogate market where externalities are included	Externalities where surrogate market is available
Social Cost of Energy	Estimates job creation (direct, indirect, induced jobs)	Social impacts, specifically local content

Table 8-5: Evaluation methods for externalities (author's analysis)

8.5 Application of measures

The technical and economic evaluation approaches available have been described in Sections 8.2, 8.3.1.1 and 8.4.2. This section attempts to apply these to offshore wind and CCGT, in an attempt to develop a FCOE for these alternatives. CCGT is taken as the alternative to offshore wind, as this is dominant alternative generation source currently on the UK Grid. This analysis focusses on marginal generation and does not attempt to attribute a value to the different intermittency and dispatchability characteristics of these technologies. This remains an important area for further work.

8.5.1 Technology readiness

The TRL measure has been described in Section 8.2, and is briefly applied here to offshore wind and CCGT, and also, for completeness, to the marine renewable technologies of tidal stream and wave.

8.5.1.1 Offshore wind - TRL

The dominant offshore wind turbine technology comprises upwind-oriented, 3 bladed turbines with gearboxes [48]. As this technology is widely commercially deployed, it is immediately apparent that it has reached TRL 9. Turbine developers continue to bring forward new and larger turbine designs, but as these are essentially evolutions of the same core technology and are offered for commercial sale, these are also considered to be at TRL 9.

Some developers, such as 2-B Energy, are seeking to develop and deploy new turbine types, which they claim offer advantages relative to the dominant turbine paradigm. These advantages are claimed to include downwind orientation (which can lead to simpler and cheaper blades, lower structure costs), full jacket structure (offering lower cost, deeper water capability), ease of access and simpler installation [191]. These alternative technologies have yet to reach TRL 9, as they are in design or prototyping stages.

8.5.1.2 CCGT - TRL

Combined Cycle Gas Turbine power generation is a well established technology, with a long commercial track record. Accordingly, it is evaluated to be at TRL 9.

As the UK Grid reacts to pressure to decarbonise, the development of abated CCGT (i.e. CCGT with pre- or post-combustion carbon capture) is likely to progress. These new developments will have to progress through the Technology Readiness Levels before commercial deployment.

8.5.1.3 Tidal stream – TRL

Tidal stream energy technologies exhibit a wide range of TRLs with some technologies apparently proven at a commercial scale, at least in the context of available revenue support mechanisms (e.g. Atlantis, Scotrenewables, OpenHydro) and others in early scale testing or prototyping stages (e.g. Minesto, Current2Current [169]).

8.5.1.4 Wave – TRL

Wave energy technologies are generally less developed than tidal stream technologies. Although large (c. 1MW scale) wave energy devices have been deployed (e.g Pelamis, Aquamarine), the research interviews undertaken confirm the view that these technologies were "too big, too soon" (to use the phrase coined by MacGillivray et al. [71] and were built this way in response to policy and revenue support drivers in place at the time.

Since the failure of both the Pelamis and Aquamarine developers, wave energy development has retrenched somewhat. Although EMEC continues to host some large scale test devices (Wello Oy's Penguin, CorPower Ocean, Laminaria [68], the majority of wave energy research and development is being undertaken by Wave Energy Scotland, which takes a measured approach to innovation, and focusses on developing technology elements before seeking to integrate these into a viable device.

As a result, it has to be said that wave energy devices exhibit a wide range of TRLs: the most advanced apparently approaching TRL 8 or 9 (e.g. Wello's Penguin), with many others across all TRL stages [68].

8.5.2 Economics

This research seeks to build up a Full Cost of Energy for each of offshore wind and CCGT. This is undertaken in three stages: evaluation of LCOE, evaluation of externalities (where possible) and assessment of qualitative effect of other externalities.

8.5.2.1 LCOE – offshore wind

Aldersey-Williams et al. [63] have assessed the $LCOE_{BEIS}$ for UK offshore wind farms. Their analysis used data from Special Purpose Vehicle company accounts for each wind farm, and actual performance data derived from the ROC register, to derive estimates of LCOE which they claim are more accurate than others derived from publicly stated capital expenditure figures.

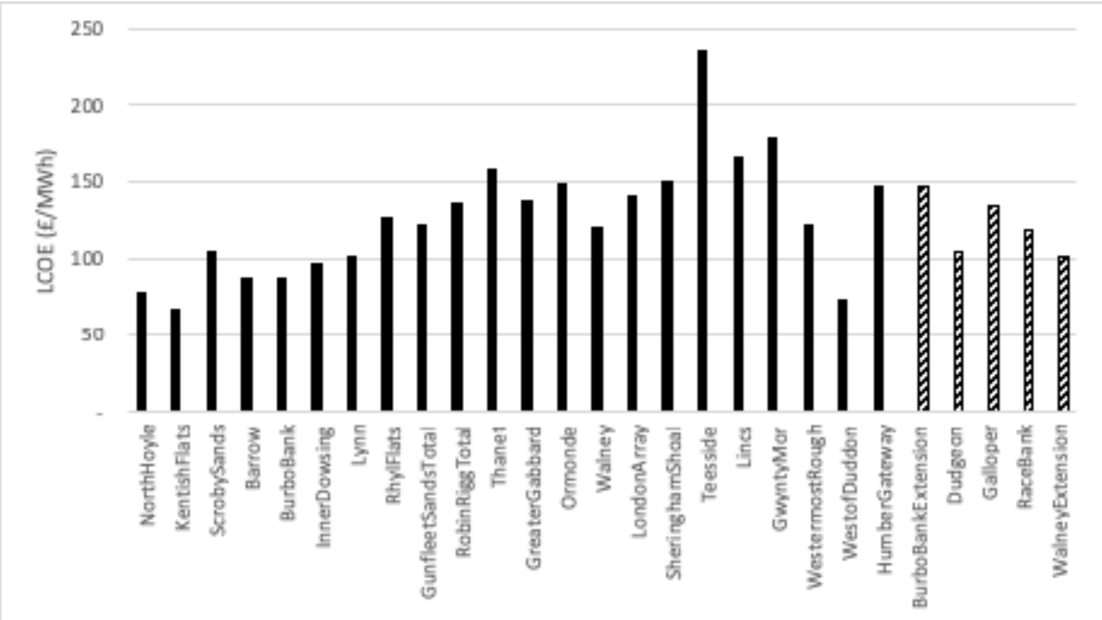

Figure 8-1: LCOE for all projects, chronological order by commissioning (authors' analysis). (NB solid bars show data for wind farms with full accounts-based and historic production data, striped where assumptions are used on capacity factor, OFTO transfer and operating costs). Source: [63]

This graph permits a number of useful observations. The first is that these publicly available data provide a useful source for detailed evaluations of this type. The second is that the levelised cost of offshore wind farms steadily increased from the first deployments (North Hoyle, Kentish Flats, Scroby Sands, all commissioned between 2004 and 2006) until the commissioning of Thanet in 2010, after which levelised costs have become more erratic but show a broadly falling trend. Thirdly, it is immediately apparent that the Teesside wind farm has an anomalously high LCOE. Aldersey-Williams et al. [63] attribute this to this project having a long and rather troubled consenting process, to using smaller turbines than had become normal by the time of its construction, and to a low capacity factor in early years of production.

The same analysis investigates the effect on LCOE of variation in the discount rate, showing that the LCOE of the most recent project, Walney Extension, is reduced from £100.24/MWh to £90.74/MWh if a more realistic discount rate of 7% is applied. This lower discount rate has been used in this research as a basis for estimating current costs for offshore wind.

Recent CfD strike prices of £57.50/MWh (in 2012 terms) suggest that offshore wind farm developers are confident of further reductions. Although, as Aldersey-Williams and Rubert [172] explain, strike prices and LCOE are not the same (as strike prices are increased by an inflation index through the life of the project, while LCOE is effectively a constant real terms price), this would nonetheless suggest significantly lower wind farm costs in future.

With 22 GW of offshore wind capacity installed at the end of 2018 [192], if the same learning rate was to be achieved in offshore wind, this would mean that the installation of an additional 22 GW would be expected to lead to a 10% cost reduction, an additional 66 GW to 20% and 132 GW to a 30% reduction in costs. The UK Sector Deal has stated an ambition to deliver 30 GW in the UK alone [47] and the Renewables Now article [192] refers to "calculations by the International Renewable Energy Agency (IRENA) which says offshore wind has the potential to reach 520 GW by 2050, suggesting that this level of installed capacity, and implicitly cost reduction, is readily within reach. Recent strike prices of £39.65/MWh for 2023/24 confirm this trend [193].

8.5.2.2 LCOE – CCGT

The same analysis by Aldersey-Williams et al. [63] calculates the LCOE for a CCGT project on the same basis, finding that its LCOE is £62.63/MWh.

8.5.2.3 LCOE – tidal stream and wave

It is not possible to undertake a similar project by project review of tidal stream or wave energy projects, as there is no population of such projects.

However, the Offshore Renewable Energy Catapult has undertaken a review of possible cost trajectories for these technologies [176] which combines levelised cost of energy analysis with ideas from learning/experience curves to assess the potential for cost reduction in these technologies. This report also addresses the industrial benefit potentially realisable by the UK, combining ideas around externalities, learning and experience curves and levelised cost of energy to fully inform an evaluation of the techno-economic context for these technologies. This report found that "tidal stream has potential to reach LCOE of £150 per MWh by 100MW installed, reducing to £90 per MWh by 1GW and £80 per MWh by 2GW" and added that further reductions were considered to be possible. Smart and Noonan noted that offshore wind projects in the UK bid strike prices were £57.50 in the most recent round of CfD bids, meaning that they were still well below the anticipated cost of tidal stream. Their report emphasised the additional value of tidal stream (and in the longer term, wave) in terms of job creation and Gross Value Added, and this theme is explored further in the discussion of externalities (see Section 8.4 et seq.).

8.5.3 Externalities

As the literature demonstrates, the quantitative assessment of externalities is feasible, but can involve costly, time-consuming and potentially unreliable methodologies. This section attempts estimates of some of the key externalities for offshore wind and competing gas-fired power generation and incorporates estimates from the literature to develop a generic value for the externalities arising from these alternatives.

8.5.3.1 Health effects of atmospheric pollution

Direct estimation of the damage costs of atmospheric pollution from power generation is feasible. The methodology developed here combines impact data (in terms of deaths/disease cases per TWh) with direct costs incurred by the NHS and generation statistics from UK Government to determine a cost per MWh.

Markandya and Wilkinson [194] evaluated the occurrence of negative health effects arising from alternative power generation technologies, including coal, gas and biomass. As shown in Table 8-6, they found that lignite had the most deleterious effect, both for the public and in terms of occupational accidents, while gas was the least damaging of the conventional thermal electricity generation technologies.

By combining these figures of health effect per TWh with the power generated in the UK [195], it is possible to determine the numbers of cases attributable to each technology (see Table 8-6).

	Coal	**Gas**	**Biomass**	**Nuclear**
Generation (TWh) [195]	65	286	93	176
Deaths per TWh [194]	25	3	5	0
Serious illness per TWh [194]	225	30	43	0
Minor illness per TWh [194]	13,288	703	2,276	N/A
Total deaths	1,583	801	430	9
Total serious illness	14,535	8,580	3,990	39
Total minor illness	858,405	201,058	211,213	N/A

Table 8-6: Health effects of electricity generation [194]

Estimation of the cost of a death is difficult and controversial. In this assessment, the cost has been taken as the same as the financial cost of treating a serious pollution-related illness (on the basis that the deceased would have had the same treatment as a person who recovered). It does not attempt to value the lost GDP contribution, or other costs, of the death.

Pimpin et al. [196] thoroughly reviewed the financial costs to the NHS in England relating to medical treatment and social care of patients whose illnesses could be attributed to atmospheric pollution. They found that the total cost of diseases attributable to airborne particulates (PM2.5) and nitrogen oxides (NO2) totalled some £157 million in 2017, and there were some 124,000 cases. The cost per case was therefore £1270. It is important to note that CCGT generation does not give rise to significant PM2.5 particulates, and Pimpin et al. did not disaggregate their data to show the damage related to each pollution type. Accordingly, the per case cost of £1270 is likely to be an upper bound for the costs of illness attributable to CCGT pollution.

In addition, it has been assumed here that each case of serious illness took the patient out of productive activity for an average of one month (20 work days). Taking average GDP per capita figures of £30,000/year [197], and assuming 220 normal productive workdays in a year, this amounts to £135/day, or £2,700 per serious illness. The total impact per case of serious illness is therefore estimated at £4,000/case. This figure is used to assess the financial cost of serious illness from atmospheric pollution from power generation, on a per MWh basis, as shown in Table 8-7.

No figures were available for the direct financial cost to the NHS of minor illnesses. Using the same approach to lost productive time as for serious illness, but assuming that each minor illness involved 5 days of lost work, this suggests that each minor illness led to £675 loss in GDP.

	Coal	**Gas**	**Biomass**	**Nuclear**
Cost per death (£)	3,970	3,970	3,970	3,970
Cost per serious illness (£)	3,970	3,970	3,970	3,970
Cost per minor illness (£)	675	675	675	675
Total cost of death (£MM)	6.3	3.2	1.7	0.0
Total cost of serious illness (£MM)	58.1	34.3	16.0	0.2
Total cost of minor illness (£MM)	579.4	135.7	142.6	-
Per MWh breakdown				
Cost of death (£/MWh)	0.1	0.0	0.0	0.0
Cost of serious illness (£/MWh)	0.9	0.1	0.2	0.0
Cost of minor illness (£/MWh)	9.0	0.5	1.5	0.0
Total health cost (£/MWh)	10.0	0.6	1.7	0.0

Table 8-7: Economic cost of health effects (author's analysis)

This approach is inevitably approximate, but nonetheless shows that the health cost per MWh for coal fired generation (estimated at £10/MWh) is very much higher than for other options, with the health cost of gas (£0.6/MWh) essentially negligible in the context of BEIS's estimate of its LCOE at £45/MWh (for gas) [198]. Biomass, with its higher particulates emissions than gas, has a measurably higher health cost than gas, and this too should be included in relative assessments.

It is immediately apparent that wind, tidal stream and wave have no health effects as they produce essentially no pollution when in operation.

This analysis does not consider health effects which may arise during the construction phase, for example from pollution arising from manufacturing processes (or from the energy required to power those processes). These are expected to be small in the context of operational effects but suggest a direction for further research.

8.5.3.2 The cost of carbon emissions

Carbon emissions are now accepted by the vast majority of scientists [38] as being responsible for the majority of climate change in recent times. But while the cost of pollution from NOx, SOx and particulates is relatively quantifiable, as it leads to health effects with measurable costs, the cost of carbon emissions is much harder to assess.

Undertaking a direct assessment of their negative externality is far beyond the scope of this work. Fortunately, others have undertaken significant work in this space.

In 2007, the UK Government adopted a Shadow Price of Carbon (SPC) to be used in policy appraisal and evaluation [199]. Initially, this SPC was set with reference to the Social Cost of Carbon, as determined by the Stern Review [179], which adopted a damage cost basis. The Government clarified that "The social cost of carbon (SCC) measures the full cost of an incremental unit of carbon (or greenhouse gas equivalent) emitted now, calculating the full cost of the damage it imposes over the whole of its time in the atmosphere. It measures the externality that needs to be incorporated into our decisions on policy and investment options. The SCC matters because it signals what society should, in theory, be willing to pay now to avoid the future damage caused by incremental carbon emissions" [179]. This approach resulted in the adoption of a Shadow Price of Carbon of £25/tCO_2e in 2007 [199].

In 2009, the UK Government changed its carbon valuation approach to a control cost basis, explaining that the previous approach, which was "based on estimates of the SCC, should be replaced with a target-consistent approach, based on estimates of the abatement costs that will need to be incurred to meet specific emissions reduction targets [200]. The case for change is motivated by the considerable uncertainty that exists surrounding estimates of the SCC." The new approach resulted in a traded carbon price of £25/tCO_2e in 2020 (with a range of £14-£31/tCO_2e), and a price for non-traded carbon of £60/tCO_2e in 2020.

Traded carbon prices relate to carbon emissions from industrial sectors controlled by the EU Emissions Trading System ("EU ETS"), while non-traded prices relate to sectors not governed by the EU ETS. The former are based on estimates of the future value of EU emissions allowances ("EUAs"), while the latter are based on the estimates of marginal abatement costs required to meet a specific emission reduction target. The sectors governed by the EU ETS include large scale power generation and heavy industry [201].

In 2014, President Obama directed the resources at his disposal to develop estimates of the "Social Cost of Carbon", taking into account climate change, disruption to ecosystems, affected crop and livestock yields, health effects increased flooding, more extreme weather events, reduced biodiversity and other factors [202]. This work resulted in a Social Cost of Carbon central estimate of \$36/tCO_2e, with a range from \$11-\$105/tCO_2e for 2015 (although the same source points out that the Trump administration may be working to reduce the SCC for US Government use).

It is reassuring that the central estimates in the UK and US are comparable at around £25/tonne CO_2, and this figure has been used in this work.

This price per tonne of CO_2 can be converted into a price per MWh, by adjusting for carbon intensity for alternative power generation technologies. Carbon intensity is defined as tCO_2e/MWh, and figures have been drawn from Weisser's work [203].

These are combined with the carbon price to give an approximation of the value of the carbon emission externality per MWh (see Table 8-8).

Technology	Tonnes CO_2e/MWh	Cost of CO_2e per MWh
Pulverised fuel coal (PF)	0.75 - 1.25	£19 - £31/MWh
Integrated coal gasification combined cycle (IGCC)	0.65 - 0.8	£16 - £20/MWh
Combined cycle gas turbine (CCGT)	0.3 - 0.42	£7.5 - £10.5/MWh

Table 8-8: Carbon intensity and carbon price per MWh (author's analysis)

8.5.3.3 Other externalities

Table 8-9 sets out the externalities identified in Section 8.4.1 and qualitatively rates whether each offers an external benefit or cost for each of the technologies of offshore wind and CCGT. The table has been colour-coded so that where offshore wind offers a benefit (or reduced cost) relative to CCGT, the row is coded green, and in the reverse case, the row is coded red. The rightmost column indicates whether this externality has been valued explicitly in Sections 8.5.3.1 and 8.5.3.2.

Externality	Offshore wind		CCGT		Eval?
	Impact	Comments	Impact	Comments	
Fuel independence	++	Offshore wind uses indigenous resource	--	UK gas reserves limited, import already required	No

Externality	Offshore wind		CCGT		Eval?
	Impact	**Comments**	**Impact**	**Comments**	
No fossil fuel needed	++	Self evident	--	Self evident (although possible role for gas as a transition fuel)	No[15]
Independence from oil/security of energy supply	++	Self evident	--	Self evident	No
Coherent environmental policy	+	Offshore wind contributes to coherent response to "climate emergency"	--	Gas has limited contribution to coherent environmental policy	No
Reduced number of blackouts	-	Without mitigation measures, offshore wind's intermittency reduces its value to the National Grid	+	Gas fired power is "dispatchable" and more responsive	No
Building awareness of environmental and climate change issues	+	Visible operating wind farms offshore help to build awareness of climate change issues (although less than onshore or solar)	+/-	"Business as Usual" does not change awareness of environmental issues	No
Motivating the public to modify their energy behaviours	+	Demonstration of national / Government commitment on climate change may impact individual behaviour	-	"Business as Usual" suggests that climate change issues are not problematic, public unlikely to change behaviours	No
A feeling of involvement in electricity generation	+/-	Large scale offshore wind developments offer little scope for public involvement	+/-	No scope for public involvement in CCGT generation	No

[15] Could potentially be evaluated through Monte Carlo analysis of possible ranges of fuel prices based on alternative geopolitical scenarios

Externality	Offshore wind		CCGT		Eval?
	Impact	Comments	Impact	Comments	
		(unlike community led onshore projects)			
Support for political parties with whom voters agree on electricity policy	+/-	Voters may agree or disagree: considered to be neutral	+/-	Voters may agree or disagree: considered to be neutral	No
Royalty fund for green purposes	+	Depending on funding structure	+	Possible, but not known	No
Job creation	+	Some local jobs created, mostly O&M	+/-	Some potential for local jobs during construction; little during operation	No
GVA	+/-	Significant parts of value imported (eg WTGs, foundations, installation), some local job potential	+/-	Significant parts of value imported (eg turbines, other equipment), some local job potential	No
Export potential and future market value	+/-	Most technology imported, local skills in installation, O&M (high market value)	+/-	Most technology imported, local skills in installation, O&M have little export potential	No
Transfer of some electricity revenue to local community earmarked for nature conservation	+	Some emerging tradition of contribution to local communities	+/-	No requirement for contribution to local communities	No
Type of ownership	+/-	Owned by large corporates	+/-	Owned by large corporates	No
Stakeholder consultation	+	Planning process requires consultation with stakeholders	+	Planning process requires consultation with stakeholders	No
Recreational activities associated with an artificial reef	N/A	N/A	N/A	N/A	No

Externality	Offshore wind		CCGT		Eval?
	Impact	Comments	Impact	Comments	
Changing social attitudes to renewables	+	Visibility of operating wind farms demonstrates importance of renewables	+/-	"Business as usual" will not affect social attitudes	No
Increased social cohesion in communities benefiting from renewables projects	+/-	Limited community benefit in additional to local jobs	+/-	No community benefit (other than local jobs)	No
Technological improvements in oil & gas from offshore wind	+	Installation, mass fabrication, offshore O&M delivery have potential to benefit oil & gas	+/-	Established technology with limited application in oil & gas	No
Increased development of battery technology in response to market demand from renewables	+	Battery technology already being trialled in conjunction with offshore wind (e.g. "Batwind" [204])	+/-	No battery technology improvements required for dispatchable technology	No
Adoption of contractual structures and commercial terms from offshore wind into oil & gas	+	Limited value	+/-	No contractual improvements required for dispatchable technology	No
New legal precedents	+	Likely to be of limited value (although with legal precedents, estimates are hard)	+/-	No new precedents likely as legal framework well defined	No
Avoiding emissions in general	+/-	No emissions so no impact	--	All emissions have negative impact	No
Avoiding greenhouse gas emissions	+	Offshore wind displaces emitting thermal technologies	--	Business as usual generates carbon emissions	Yes
Improvement of air quality (impacts on	+/-	Very limited emissions (some attributable to	--	Emissions of SOx and NOx have significant cost	Yes

Externality	Offshore wind		CCGT		Eval?
	Impact	Comments	Impact	Comments	
visibility, acid rain, respiratory problems)		manufacture, installation and O&M), so limited impact			
Avoiding environmental drawbacks of coal	+/-	No differential impact vs CCGT	+/-	No differential impact vs offshore wind	No
No water used	+/-	No cooling water required	-	Some cooling water required	No
Effects on biodiversity	-	Disputed but likely to have some effect on local biodiversity due to environmental perturbation	-	Likely to have some effect on local biodiversity due to environmental perturbation	No
Effects on habitat and flora	-	Disputed but inevitably some impact on local habitats (offshore and onshore) and flora in onshore infrastructure (grid connection substations, operations bases etc)	-	Inevitable negative impact as construction and site works often impinge on greenfield sites	No
Effects of fauna and bird life	-	Uncertain impact, but inevitably some impact on local fauna and bird life	-	Possible negative effect on local fauna and birdlife through environmental perturbation	No
Terrestrial visual impacts	-	Limited visual impact on shore (grid connection substations, operations bases etc)	-	Visual impact, new build greater than re-powering of existing site	No
Marine/coastal visual impacts	-	Despite efforts to make into a tourist attraction (e.g. Scroby Sands), overall visual impact is negative	+/-	No offshore impact	No

Externality	Offshore wind		CCGT		Eval?
	Impact	Comments	Impact	Comments	
Visual impacts associated with residential proximity	+/-	Not likely to be situated near residential areas	+/-	Generally not situated near residential areas	No
Noise impacts	+/-	No noise impact onshore	+/-	No known noise impact issues	No
Green policy	+	Offshore wind demonstrate and build support for environmental policy	+/-	No impact on policy	No
Location	+/-		+/-		No
Land area effects	+/-		+/-		No

Table 8-9: Impact of externalities (author's analysis). Key: ++ Strong positive, -- strong negative, - negative, + positive, +/- neutral

It is immediately apparent that offshore wind appears to generate more positive externalities than CCGT, although in most of these cases, the relative values of these externalities has not been estimated.

8.5.3.4 Externalities - conclusion

The key externalities evaluated, and the technology for which they have been assessed are shown in Table 8-10.

Externality	Offshore wind	CCGT
Health effects from atmospheric pollution	Zero	Cost: £0.60/MWh
Carbon emissions effects	Zero	Cost: £7.50-£10.50/MWh
Visual disamenity	Negligible	Not evaluated
Others	Mainly positive or neutral	Mainly negative or neutral

Table 8-10: Externalities evaluated (author's analysis)

8.5.4 Economic conclusions

An economic comparison of offshore wind and CCGT can be made by combining LCOE estimates with evaluation of the externality costs and benefits where these are available.

LCOEs for the two technologies are set out in Sections 8.5.2.1 and 8.5.2.2, and are set out in the solid blue bars in Figure 8-2.).

The value of those externalities for which reasonable estimates are derivable from the literature (Section 8.5.3) have been added to these blue bars. These only relate to CCGT, where but the additional cost of quantifiable externalities adds £8.10-£11.10/MWh (range from Section 8.5.3.2, depending on low case or high case) to the LCOE. These externalities are costs, adding to the LCOE, and are shown in orange (low case) and red (high case).

By definition, it is not possible to evaluate the unquantifiable externalities, but it is important to note that the unquantifiable externalities for offshore wind were seen to be positive or neutral, thereby reducing the FCOE by an unquantifiable amount, while for CCGT they appeared to be negative or neutral, thereby increasing FCOE for CCGT. These "directional" but unquantifiable externalities are shown as arrows on Figure 8-2.

In summary, offshore wind's FCOE is evaluated to be the same as its LCOE at £90.74/MWh, as no quantifiable externalities were evaluated. As discussed in Section 8.5.2.1, wind farm developers are clearly expecting further reductions in offshore wind LCOE to around the level of current strike prices: £57.50/MWh.

The FCOE for CCGT was calculated at its LCOE of £62.63/MWh (see Section 8.5.2.2) plus the externality costs of £8.10-11.10, making a total of £70.73/MWh – 73.73/MWh.

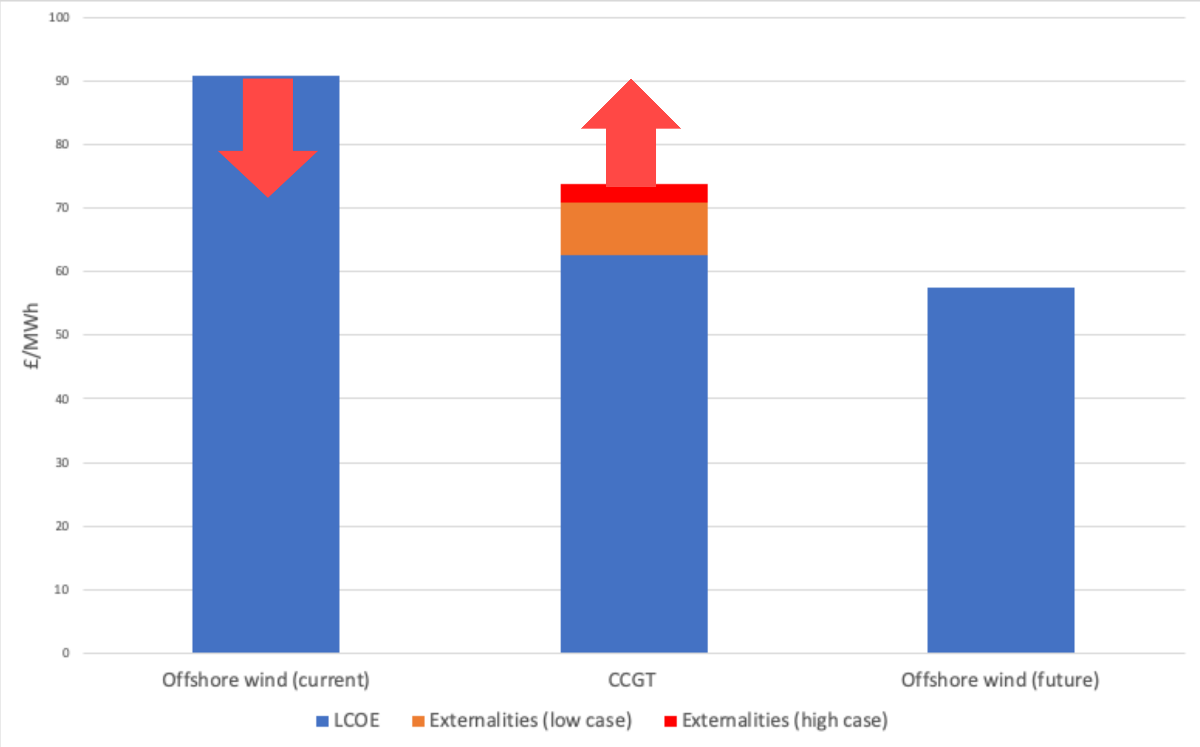

Figure 8-2: FCOE for offshore wind and CCGT (author's analysis), impact of unquantified externalities shown by arrows (not to scale)

Figure 8-2 shows two critical conclusions. The first is that the expected trajectory of offshore windfarm LCOE (even excluding externalities) is to become cheaper than CCGT. Once again, it is important to recognise that this analysis is valid for marginal generation capacity: it does not take account of the potential system costs of managing offshore wind's intermittency to match the flexible dispatchability of CCGT.

The second critical conclusion is that if externalities are taken into account, in the context of LCOEs for current projects, offshore wind may not be much more costly per MWh than CCGT and may already be cheaper once the full range of externalities is taken into account.

8.6 Conclusions

This chapter sets out potential technological and economic measures for relative value potential, and proposes a new measure – Full Cost of Energy, or FCOE – which combines the known strength of levelised cost of energy with the evaluation of externalities.

The proposed FCOE measure is evaluated for offshore wind and a counterfactual of CCGT. This finds that the cost of offshore wind is approaching competitiveness with CCGT at current cost levels, as the externalities for offshore wind tend to be positive, while those for CCGT (and other thermal technologies) are more often negative.

If offshore wind can achieve cost levels implied by the most recent CfD strike prices, it appears that it is already cheaper than CCGT, even excluding externalities. The inclusion of externalities would make offshore wind still more attractive.

This cost trajectory shows that offshore wind is demonstrating very strong relative value potential in the context of the most dominant competing technology – CCGT, and it is suggested that it is this strong showing that has contributed to the emergence of offshore wind as a powerful force in the UK energy mix.

9 Collateral findings

Chapters 5-7 explored the key research question of whether the "seven functions" model of TIS provides a complete framework with which the characterise the emergence of the focal technology in a TIS. This chapter adds to that with a discussion of additional findings resulting from this research and is structured in 2 sections.

Section 9.1 is a discussion on the experience of applying the TIS seven functions model and offers some thoughts on its merits and drawbacks. It goes on to suggest how the extension of the seven functions model with the introduction of the eighth function of relative value potential might offer a route to a partial reconciliation of TIS and MLP, although it notes that different philosophical underpinnings may always present obstacles.

Section 9.2 takes a different tack and discusses the comparative emergence of offshore wind relative to tidal stream and wave energy. This discussion addresses the current challenge facing these latter technologies: the question of how to make a supportable case for continuing Government policy and financial support.

9.1 The experience of TIS

This research tested the architecture of the "seven functions" model of TIS, rather than aiming to operationalise it. Nonetheless, the researcher formed some views on the strengths and weaknesses of this aspect of TIS.

9.1.1 Use and usefulness of TIS

The depth and variety of literature on Technological Innovation Systems points to the usefulness of the approach. This research complements that literature by working with stakeholders in the focal technologies, who had not previously been much involved in the application of TIS thinking.

The research confirmed the explanatory power of the TIS approach and the validity of the model. Stakeholders agreed that the TIS model had potential to explain the evolution of the TIS. Other authors, such as Hannon et al. [97]and Hekkert and Negro [116] have shown that operationalisation of the seven functions model can be achieved, although neither actually tested the validity of the functions they chose to use with a relevant stakeholder group.

It would be interesting to undertake a quantitative comparison of the relative levels of functional completion for each of offshore wind, tidal stream and wave, to see if this pointed to any specific reasons for the differences in niche break-out achieved. Unfortunately, this is beyond the scope of the current research.,

A particular weakness of the TIS approach, as applied through the seven functions model and as shown in this research, is that it fails to take adequate account of the changing context into which the focal technology is emerging. This research proposes that a new, eighth function – relative value potential – may go some way to addressing this weakness, by forcing the model to look outside the focal technology itself and into the competitive world in which it hopes to establish an existence.

9.1.2 A route to reconciliation between TIS and MLP?

This research has found that the "functions" approach can offer insights into the detailed processes of niche break-out, especially when reinforced with the proposed new function.

In contrast, the Multi-Level Perspective clearly defines the static, dynamic and contextual aspects of the socio-technical system, by defining the regime, niches and landscape respectively, but does not clearly address the specifics of how niche technologies can break-out into what Geels [82] would call the "regime".

The proposed new function explicitly forces consideration of the evolution of the TIS to take account of "landscape" and "regime" factors – in other words, forcing a consideration of the value potential of the focal technology relative to incumbent or other emergent technologies. This suggests that the new function may offer a route to a partial reconciliation of TIS and MLP.

With the proposed addition of the new function, the extended functions approach could be applied to a focal technology, operating in what Geels [82] would characterise as a "niche", to throw light on the precise mechanisms which permit (or prevent) niche technologies to break out into the "regime" layer whilst also considering the enabling or blocking roles of incumbents in the socio-technical regime and of "landscape" factors.

Through this extension, the TIS functions approach could be extended to consider the effect of the exogenous (to the niche) actors on functional success.

As the field continues to develop, clarity as to the underlying methodological approach, where a tension between interpretivist (MLP) and positivist (TIS) has given rise to reciprocal criticisms between MLP and TIS practitioners in the past (see Geels [104]), will also be essential. This research has found that a pragmatic approach, positivist where possible and interpretivist where necessary, has nonetheless made useful findings.

Figure 9-1 shows the Geels et al. [82] characterisation of the Multi-Level Perspective niche/regime/transition framework overlain with the functions approach from TIS. The proposed integration of the functions approach into the MLP conceptual architecture, through the introduction of the new function of relative value potential, is new and is offered as a contribution to the literature.

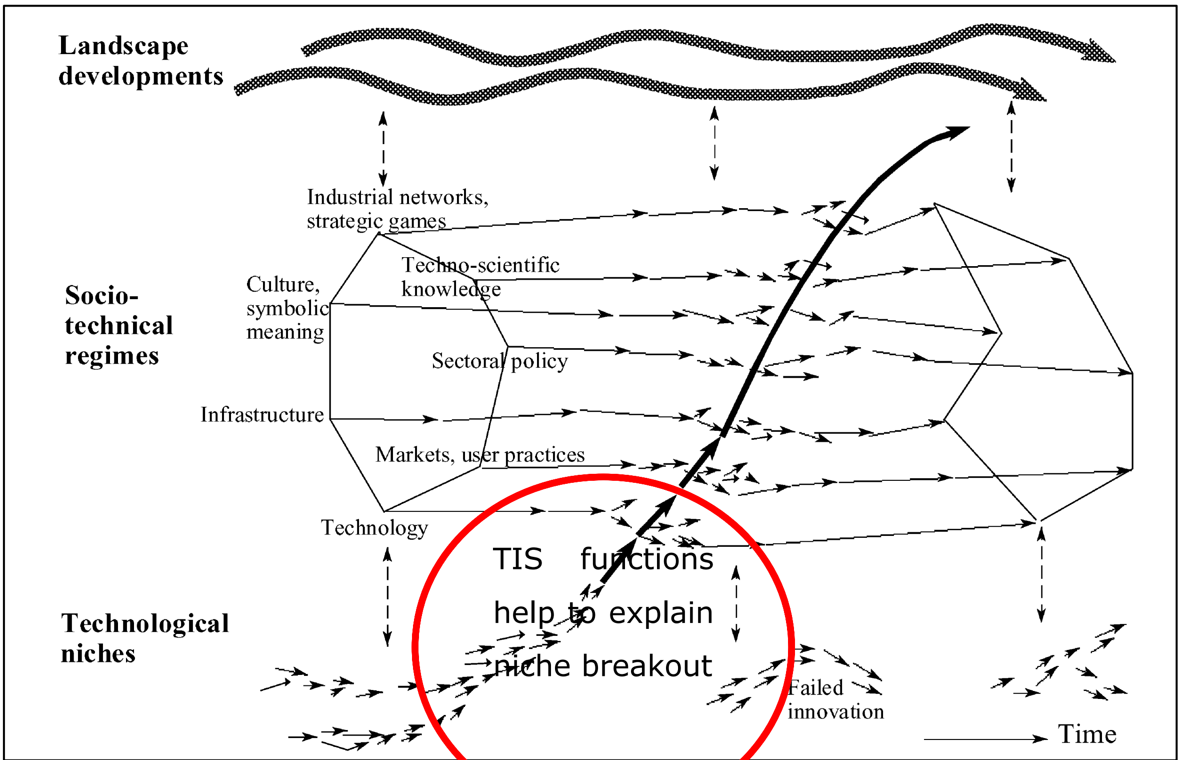

Figure 9-1: From Geels (2002), author's modifications

9.2 Learnings for marine renewables

The final research question asked whether there were learnings for marine renewables arising from the emergence of offshore wind.

This section considers that question in two parts: the first compares the development of marine renewables with offshore wind, and the second discusses whether marine renewables should consider itself to be competing against offshore wind or other technologies.

In order to address this question, it is first necessary to understand that likely levelised cost evolution of marine renewables technologies. The cost reduction trajectory suggested for tidal stream, as described in the ORE Catapult report [150] (see Figure 9-2) effectively never reaches a level of LCOE below £90/MWh, while offshore wind is already bidding at levels less than half of this [193].

The same report makes similar claims for the potential cost reduction trajectory for wave energy but accepts that the timescale is likely to be ten years later than for tidal stream.

It is within this context that the learnings for marine renewables emerge.

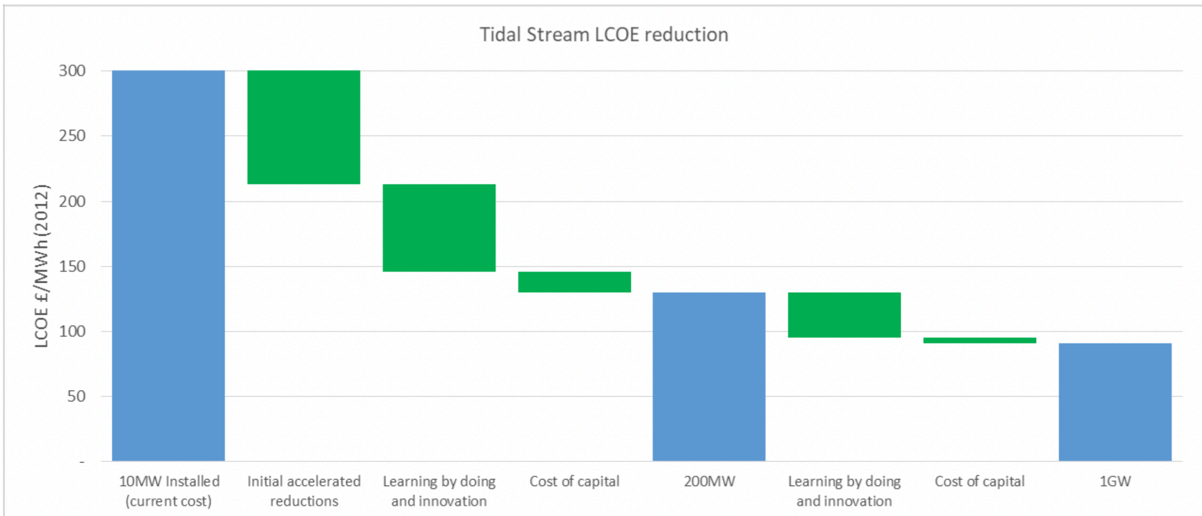

Figure 9-2: Tidal stream LCOE reduction; source: [150]*, Figure 1*

9.2.1 Comparative review of offshore wind and marine renewables

Consideration of marine renewables and offshore wind starts with an assessment of the differences in how they have achieved each of the seven Hekkert functions.

This leads to findings on how marine renewables might make a competitive case for support, and thereby achieve niche break-out.

9.2.1.1 Comparative functional review

The analysis of the interviews, as set out in Chapter 5, has confirmed the necessity of the core seven functions in both offshore wind and marine renewables. While it was not within the scope of this research to attempt to formally evaluate the degree to which each function had been achieved, a subjective assessment (summarised in Table 9-1 and based on the interview analysis) suggests that progress in F1, F2, F3 and F7 was advanced for both technology families, but that F4 was strongly differentiated, leading to strong differential performance in F5 and F6.

Function	Offshore wind	Marine renewables
F1	Well established entrepreneurial activities throughout supply chain	Multiple technology developers at work
F2	Active throughout the supply chain	Active for developers with funding.
F3	Limited. Intense competition for sites, turbine sales	Limited. Developers with funding have little incentive to share and strong investor pressure not to
F4	Strong. Recently announced Sector Deal describes roadmap for offshore wind roll out	Poor. Developer community seeking to build rationale for support with Government
F5	Good. Sector Deal describes Government commitment to support through Contracts for Difference	Poor. Financial incentives are essentially inaccessible for most technology developers. Some EU support
F6	Good. Active supply chain, good visibility of future demand	Poor. No visibility of route to market means supply chain fails to engage
F7	Mixed public support	Strong public support

Table 9-1: Comparative subjective assessment of functional delivery: offshore wind vs marine renewables (author's analysis)

It appears that both technology families have enjoyed active entrepreneurship and development of (often unshared) knowledge, but that policy support has co-evolved with technology development to offer differentiated support for the technologies (see Table 7-1).

However, as the interviews made clear, the marine renewables community is still committed to developing its technologies and achieving niche break-out. On the basis of levelised cost, it is hard to see how a competitive case can be made, so marine renewables must find other areas of differential benefit in which they can compete.

9.2.1.2 Differential benefits of marine renewables relative to offshore wind

Some areas in which tidal stream and wave could potentially make a case for support through their offering of additional externality benefits relative to offshore wind are set out below:

- **Political benefit:** creation of jobs and wealth in often-challenged coastal areas can be claimed as political success
- **Gross Value Added:** as supply chain establishes
- **Export potential:** as industry "nucleates" in UK
- **Job creation:** with potentially high value manufacture, installation, operation and maintenance jobs
- Complementary intermittency and better forecastability (tidal stream only)
- Negligible visual intrusion
- **Breakwaters:** coastline management and storm impact mitigation (wave only)
- **Smaller minimum economic size:** minimum size for offshore wind turbine is realistically 5 MW, so wave or tidal might economically serve smaller communities with demand less than this level

It is in these areas of differential externality benefit that marine renewables must concentrate their arguments, if they are to attract and retain Government policy support. One interviewee made the point that the marine renewables industry was working this point with Government:

"We think the benefits arising could be similar in terms of number of jobs, the types of jobs and specificity of high end technical engineering offshore skill jobs." – MPD72

The Minister of State's letter [154] appeared to accept this point, by allowing for a "rationale for funding" to be presented:

"The Department is continuing to engage with wave and tidal stream developers to understand their cost-reduction trajectories, where those savings are likely to be found and, importantly in light of declining costs for other renewables, whether there may be a rationale for funding arrangements outside of the CfD." – Claire Perry, Minister of State for Energy [154]

By inviting "a rationale", the Minister's letter can be read as offering potential for funding support if sufficient externality benefits could be demonstrated, thereby making marine renewables competitive with other renewables if externalities were included. Put another way, if the externality benefit of marine renewables more than compensated for their higher unit cost of electricity, that could present a rationale for their support.

9.2.2 Referencing marine renewables to other technologies

The Hinkley Point C nuclear power station, currently under construction, was awarded a contract for difference at an initial strike price of £89.50/MWh [58] for a term of 35 years. It is expected to start production in 2025.

Government's Clean Growth strategy [43] anticipates the successful completion of Hinkley Point C and progressing "discussions with developers to secure a completive price for future projects in the pipeline" [205].

This suggests that the Government may tolerate prices above those offered by other generation options and may allow marine renewables to make a case for support at price levels above those of offshore wind. However, as the Government's Clean Growth Strategy states that "we need to bring down the costs of nuclear power", the downward pressure on electricity generation costs implicit in the "energy trilemma" remains a powerful force in policy making and option selection.

Accordingly, marine renewables might consider positioning itself as a competitor with nuclear, offering a number of differentiated benefits at a higher price than offer shore wind.

The differentiated benefits offered by marine renewables relative to nuclear might include:

- **Public acceptability:** is very high for marine renewables (79% support offshore wind, wave and tidal), much lower for nuclear (33% support) [161,205]
- **Waste/decommissioning:** limited waste, simple decommissioning for marine renewables, long lived and costly challenge for nuclear
- **Gross Value Added:** marine renewables more likely to nucleate local supply chain, nuclear technology largely imported
- **Reliability:** currently proposed nuclear technologies unproven, single failure could materially impact UK energy balance: marine renewables more distributed, making single failure less impactful
- **Cost of entry:** test/demonstration costs for marine (c. 10s of MW) much less than for nuclear (c 3 GW)

At a smaller scale, positioning marine renewables in competition with other high cost forms of generation is also valid. For example, EC-OG Limited and Current2Current Limited (both Aberdeen tidal device developers) have identified that offshore oil wells may require a local source of power, often at limited levels. They have further identified that the cost of delivering this power through power umbilicals can be very might, and that this creates a market opportunity for localised tidal stream power in service of this demand. Both companies are pursuing this niche [206,207].

Similarly, AlbaTERN has installed and operates a small and low-power wave energy installation in Mingary Bay, Ardnamurchan in Scotland. This array supports a local aquaculture business and shows that a market may exist to displace costly diesel generation whilst enjoying a comparable unit electricity price to the diesel alternative [208].

9.2.3 Conclusions on learnings for marine renewables

The review here, built on the interview findings, suggests that marine renewables should adopt a strategy of building a case for continuing funding support by focussing on the differential benefits offered by marine renewables technologies over the potential alternatives of offshore wind and nuclear, and that viable market niches may exist, albeit at kW scales rather than "utility" MW scale.

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10 Conclusions

This chapter concludes this thesis and is set out in 7 sections: Section 10.1 rehearses the rationale for this research and its theoretical framing. Section 10.2 reviews the first part of the key research question: are the "seven functions" necessary? Section 10.3 is complementary and addresses the question of whether the seven functions are sufficient. Section 10.4 builds on Section 10.3 and outlines ways in which the proposed new function of relative value potential could be assessed.

The concluding Sections, 10.5 and 10.6 then restate the research questions and objectives, and describe the research findings in this context, identifying contributions to the literature which have arisen through this work.

The thesis concludes in Sections 10.7 and 10.8 by discussing the strengths and limitations of this research and identifying areas for further work.

10.1 Basis for research

This research took shape in an attempt to answer the question of how technological change and associated socio-technical transitions took place – a question of perennial validity during the author's 35 year career in the energy industry.

This wide-ranging subject was honed into the main research question that this thesis addresses: "does the 'seven functions' model of Technological Innovation Systems theory provide a necessary and sufficient framework to explain the emergence of marine renewables in the UK?".

After a review of the literature, and specifically a consideration of both the Multi-Level Perspective and Technological Innovation Systems, the research focussed on TIS theory, as this appeared to offer a robust framework within which to consider the broader question and seemed to offer a better route to operationalisation. However, the apparent tension between MLP and TIS remained in the author's mind, and to the extent that a reconciliation was possible, this was an aim.

Early in the research, serendipity (technically Mertonian Serendipity under Yaqub's taxonomy [209]) played a part, as the author was invited to peer review Hannon et al.'s report [97] which applied the TIS functions model to wave energy innovation policy. This review provided some critical insights which informed this research.

10.2 Necessity of functions

This research reviewed the literature and found that there were many proposed functions inventories available in the literature. However, analysis of these inventories, set out in Chapter 4, suggested that Hekkert's inventory [95] captured the key aspects proposed by other researchers. This is not to say necessarily that it is the "best" inventory, but that it seemed to offer sufficient breadth for the research.

The validity of these functions and their necessity was strongly supported by the analysis of the interviews, as set out in Chapter 5. There were no noteworthy differences in the perceived importance of the functions between different stakeholder groups (Wind Turbine Manufacturers, Policy Makers etc.), and all of the seven functions were highly scored by interviewees.

F4 – Guidance of the Search was seen to be the single most critical function for delivery of the TIS. This suggests that Government support was widely seen to be essential for the emergence of a new technology. In the case of offshore wind, positive policy support had led to a successful emergence, while in marine renewables, inconsistent policy and support had not enabled a comparable process.

10.3 Sufficiency of functions

The analysis of the interviews, and the review of literature suggested, however, that the seven functions were not a sufficient framework to fully explain the emergence of offshore wind and the relative failure of tidal stream and wave to achieve a similar break out.

This analysis found that a new function, which has been named "Relative Value Potential" was supported. This function has been defined as **"the potential or actuality of the focal technology in the TIS being competitive with relevant incumbent or emergent technologies"** and is described in depth in Chapter 6.

10.4 Evaluating Relative Value Potential

Chapter 7 considered potential metrics for Relative Value Potential in some detail. As the function deliberately considers contextual factors, in attempting to assess the value potential of the focal technology relative to incumbent or other emerging technologies, it is important that it is evaluated in a relative way.

Accordingly, Chapter 7 proposes that an extension of the widely-used Levelised Cost of Energy (LCOE) measure be adopted. Full Cost of Energy (FCOE) adds an externality term to the LCOE calculation, to enable a full comparison of the merits and drawbacks of technology alternatives.

An example calculation of FCOE is attempted, comparing offshore wind with CCGT-fired generation, and including the health and carbon costs of the carbon-emitting choice. This shows that while offshore wind is still the costlier alternative, the inclusion of externalities closes this value gap, and the unquantifiable externalities probably act to close the gap still further.

10.5 Research objectives and questions

Section 2.10 set out the objectives and research questions in this work. Table 10-1 summarises them, and comments on how they have been met, and in which section of the thesis this is set out.

Research objective	Comments	Chapters / Sections
To identify any consensus characterisation of the seven functions model in the literature and refine it in the light of research findings	A number of functions inventories were identified in the literature, and refined into a seven functions inventory after Hekkert et al. [95]	4
To assess the perceived relative importance of the seven functions among stakeholders in the UK offshore renewable energy sector	The interviews were analysed to determine the interviewees' perceptions on the importance of each of the seven functions.	5
To assess the completeness ("sufficiency") and appropriateness ("necessity") of the seven functions model in describing the emergence of offshore wind, tidal stream and wave in the UK	Necessity was confirmed by the qualitative and quantitative assessment of the interviews; qualitative textual analysis of interviews for sufficiency found it unproven	5 and 6
To identify, justify and define any additional functions emergent from this research	Qualitative textual analysis identified requirement for additional function of "relative value potential" which was defined, justified and measures identified and proposed	6 and 8
To consider whether these findings offer any potential for reconciliation between the TIS and MLP approaches	The proposed new function forces consideration of factors beyond the focal technology, in Geels' "regime" and "landscape", and this demonstrates some scope for reconciliation and/or combination of these approaches	9.1.2
To identify findings of relevance to the wave and tidal stream sectors from the specific findings on offshore wind	The interview analysis, together with a separate paper [63] found that offshore wind's LCOE is declining fast and that tidal stream does not expect to catch up. This led to the conclusion that marine renewables will have to identify differential externality benefits relative to offshore wind if they are to regain policy support	9.2

Table 10-1: Research objectives reviewed (author's analysis)

This research finds that the achievement of these objectives has allowed the research questions to be addressed. Table Table 10-2sets out the research questions and describes how each has been addressed.

Research question	Findings and comments	Chapters / Sections
Is there a consensus characterisation of the seven functions model?	This research finds that different researchers have proposed different, although often closely related, inventories of functions. There is therefore a weak consensus on functions and this research proposes that Hekkert et al.'s [95] functions inventory is adopted	4
Are the seven functions necessary and sufficient to describe the socio-technological changes under consideration?	This research finds that the seven functions in the Hekkert inventory are all necessary, as supported by the interview findings, but that they are not sufficient to fully characterise the socio-technological transition	5 and 6
What is the perceived importance of each function in delivering the transition?	All of the seven Hekkert functions are perceived to be necessary, and all score more than 2.5 on a five point modified Likert scale. The most important was seen to be F4 – Guidance of the Search, although this result was not statistically significant	5
If these functions are not sufficient, what other function(s) are required?	This research found that analysis of the interviews suggested that an additional function would help to characterise the transition. This function has been defined as "relative value potential value"	6 and 7.1 - 7.3
How should any additional functions be characterised?	The proposed new function of relative value potential has been defined and a number of measures proposed and discussed. One specific measure – "Full Cost of Energy" has been defined and tested	8 - 8.5
Is there scope to reconcile or integrate TIS and MLP approaches?	The definition of the proposed new function may offer a route to some reconciliation, as it provides a means of evaluating how niche breakout can be assessed	9.1.2
What lessons are relevant to the emergent wave and tidal stream sectors from the offshore wind experience?	The research found that to achieve niche breakout, a new technology has to deliver one all of the seven Hekkert functions and the proposed new function	9.2

Table 10-2: Research questions reviewed

10.6 Contributions to the literature

This research has made contributions to the literature in methodology and in the definition of the TIS model and its application.

10.6.1 Methodology

This research adopted a novel methodology in relation to applying the TIS functions model. The literature review (Section 2.3.3) noted that the inventories and definitions of functions found in the literature were generated by the researchers themselves, from these researchers' own understanding and interpretation of socio-technical transitions.

This research makes two methodological contributions. The first was to build an inventory of functions from a review of the various functions lists proposed in the literature. It is suggested that this list is perhaps more complete and supportable than others in the literature, as it has been built in this comprehensive manner.

Secondly, this research extends the widely-used functions approach by working with stakeholders of the TIS and the focal technology, to obtain their qualitative and quantitative views on the relative importance of the functions. Other researchers have simply presented lists of functions: this research tested one list with relevant stakeholders, showing a way to ensure that a list of functions is relevant to the transition being studied.

This new methodology confirmed that in the case of offshore renewable energy in the UK, the Hekkert functions inventory appeared to provide a necessary, but not sufficient, inventory of functions.

10.6.2 Proposed new function

A second contribution to the literature is the proposed new function of "relative value potential". The research found that the "seven functions" while necessary were not sufficient to characterise the transition. This new function is explored in detail in chapters 6 and 8.

In summary, this function requires TIS practitioners to "look outward" from the focal technology they are considering, to take account of the technical and economic context into which the focal technology aims to emerge. This perspective provides insight into the potential for the emergent focal technology to "break into" the regime, by disrupting incumbent technologies, as a result of the benefits (economic, technological and external) that it can offer.

10.6.3 LCOE review and application

This research considered metrics for this new function. This gave rise to two papers which have been published during the course of this research, and on which the author of this research was the lead author. The first considered the widely-used Levelised Cost of Energy (LCOE) metric [172], and found a theoretical basis for its use, and undertook a critical assessment of its use. This paper found that LCOE, as applied by the UK Government's Department of Business, Energy and Industrial Strategy was a useful measure, which returns a value equal to the energy price required in flat real terms for an energy technology to offer a return at the level implied by the discount rate.

The second paper evaluated LCOE for UK wind farms, based on publicly available accounting data [63]. It found that cost data widely used in the public domain were unreliable, and that cost trends for offshore wind were broadly downwards, although significant further cost reductions were required for offshore wind to compete unsubsidised with CCGT.

As the scope of these papers lies outside the main scope of this research, this work has been captured in these papers and is not restated here.

10.6.4 Proposed introduction of FCOE

The final significant contribution to the literature is the proposed introduction of the Full Cost of Energy (FCOE) metric, which extends the LCOE definition to include externalities not usually captured in comparative analysis of generation alternatives. While LCOE measures have some weaknesses, this extension potentially strengthens them.

An attempt to evaluate FCOE was made in the case of offshore wind and a counterfactual of CCGT generation (see Section 8.5.4), and this found that the externalities associated with offshore wind appeared to be benefits, while those associated with CCGT were costs, some of which were quantifiable.

10.7 Strengths and limitations of this research

10.7.1 Strengths of research

The principal strengths of this research are captured in the Sections 10.6.1 to 10.6.4 above, which detail its contribution to the literature.

Foremost among these is that this research is the first, to the knowledge of the author, to have involved stakeholders in a TIS in using the functions approach to understand the evolution of that system. This has provided a validation of the widely used "seven functions" model, and has found that an additional function might strengthen this model by forcing users to take account of the relative value potential.

Additionally, the proposed measure of FCOE is considered to be an innovative and useful tool with which comparative assessments of energy generation technologies can be undertaken.

10.7.2 Limitations of research

During the course of the research, a number of limitations were identified. Where possible, these were addressed during the course of the work, and remaining unaddressable limitations have been detailed here.

10.7.2.1 Convenience sample

The interviewees were found primarily through the author's personal network and therefore may not be fully representative of all participants in the TIS. This was addressed in part by ensuring multiple interviewees in each stakeholder group.

It is considered that the sample was acceptably representative of the various stakeholder groups (MPD (n=3), MTD (n=3), PM (n=4), SC (n=4), SH (n=7), SO (n=4),WPD (n=4), (WTG (n=3).

10.7.2.2 Unconscious "priming"

Care was taken not to "prime" interviewees by suggesting preferred outcomes for the research. It is noted that it would not have been possible to prime interviewees in relation to the question of "necessity" of the seven functions as the research began without the interviewer having a view on this question.

The coherence in scores between and within stakeholder groups suggests that the research was finding real results, and that the question of "necessity" was unambiguously answered. Further work might reinforce these findings.

The question of "priming" and potential research bias in relation to the question of "sufficiency" of the seven functions is addressed in more detail in Section 10.7.2.3 below.

10.7.2.3 Potential research bias

The apparent insufficiency of the "seven functions" model emerged rapidly in the early interviews and gained in resolution as the interview process proceeded.

There is some risk that the later interviews were unconsciously more directed in a desire for additional evidence, and that support was explicitly sought in support of the emerging hypothesis, rather than allowing evidence for the proposed function (or additional new functions) to emerge organically.

This is a risk in any grounded theory work, where new ideas emerge during the course of research and validation is sought for them as the research progresses. In this case, the strong support for the proposed new function is considered to have been sufficient to validate the proposal put forward here. It is noted that interviewees did not necessarily express support for the proposed new function in terms of "functions" and other TIS terms, but rather offered evidence consistent with the required new function.

10.8 Further work

This research has identified a number of areas for further work. These are outlined here:

- **Evaluation of functions.** This work has sought validation of the seven Hekkert functions, but it has not attempted to operationalise these functions with quantitative evaluation. This might permit the analysis of the development of tidal stream and wave relative to offshore wind (and each other), helping to understand their different levels of success.

- **Validation of the proposed new function.** Application of the research method used in this work, but including the proposed new function, would allow for perceptions of the validity of this new function to be examined. This could also develop additional possible metrics for the new function.

- **Application of FCOE.** This research proposes the introduction of a new lifetime cost of energy metric – Full Cost of Energy. While this work includes an example application of this measure, a more detailed application including other externalities besides the ones addressed here would throw light on the full relative costs of electricity generation alternatives. This might also include probabilistic "monte carlo" techniques, to allow for inclusion of externality or other factors with ill-defined values (and also potentially including future fuel prices for thermal generation, as outlined by Aldersey-Williams and Rubert [172]).

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Appendix 1 – Interview outline and structure

<u>Interview structure</u>

The research interviews were undertaken as semi-structured interviews, and therefore did not adhere to a rigid set of specific questions. Their structure was generally according to the template below:

<u>Introduction</u>

The interview began with an introduction, in which the researcher provided an overview of the purpose of the study and of the Technological Innovation Systems framework. The seven "Hekkert" functions were briefly described and the structure and duration of the proposed interview agreed.

At this stage, each interviewee confirmed their agreement to participate and with the anonymity terms.

<u>Function by function discussion</u>

Each of the functions was discussed in turn according to the following general structure:

Functional description – the researcher briefly described each function and summarised some proposals on how it might be assessed

The interviewees' views were then invited on:

- perception of the importance of each function for the transition
- what they felt were factors contributing to completion of the function
- what actors participated in the function
- possible metrics and indicators
- any other related factors or comments

The functions were:

F1 – Entrepreneurial Activity

F2 – Knowledge Development

F3 – Knowledge Diffusion and Networking
F4 – Guidance of the Search
F5 – Market Formation
F6 – Resource Mobilisation
F7 - Legitimation

The structure of the interview was not rigid, but if the discussion appeared to be drifting too far from the core subject, the "functions" architecture was used a basis to revert to the planned structure.

General discussion
Following discussion of the seven "Hekkert" functions in turn, interviewees were invited to make any other comments they felt relevant to the enquiry, including whether they felt that the seven "Hekkert" functions were an adequate explicatory framework for the transition.

Scoring
Finally, each interviewee was asked to score their perception of the importance of each function to the transition, on the five point scale described in [section].

Close
Each interviewee was thanked for their participation, reminded of the anonymity provisions and informed that they would be sent the transcript for review.

In some cases, interviewees asked for a digest of the findings in due course, and I will, of course, provide this.

Approvals
In all cases, the transcript was sent to the interviewee for approval and/or editing, and in every case written approval was received to use the transcript.

Additionally, as extracts were made from each interview for quotation, written approval for their use was sought and received in all cases.

Appendix 2 – Letter from Claire Perry, Minister for Energy and Clean Growth

Department for
Business, Energy
& Industrial Strategy

The Rt Hon Claire Perry MP
Minister of State for Energy and Clean Growth

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John Aldersey-Williams

By Email: john@aldersey-williams.co.uk

Our ref: MCB2019/07272/AC

1 May 2019

Dear John,

Thank you so much for your email dated 12 April, regarding support for marine renewable energy.

As you are aware, the Government has a long history of supporting the development and deployment of wave and tidal stream technologies in the UK. To date, we have provided sustained and targeted support, enabling the wave and tidal stream sectors to move from initial concept onto prototypes and now the first arrays. As you note, being the first facility of its kind anywhere in the world, the European Marine Energy Centre in Orkney was instrumental in facilitating much of the technology development we have seen over the last couple of decades.

Over the last decade, various bodies across Government have provided innovation/R&D funding of £175m to the wave and tidal sectors (almost £80m since 2010). This includes the large majority of the over 10MW of tidal stream devices deployed for testing in the UK. The world's first commercial scale tidal stream turbine (MCT SeaGen 1.2MW) and the MeyGen 1a array demonstration project, deployed in the Pentland Firth in 2016, were both recipients of Government R&D funding. The latter, which was the world's first megawatt scale tidal array, received a £10m BEIS innovation grant, alongside other public support, and is receiving support under the Renewables Obligation (RO) at 5ROCs/MWh.

However, while Britain has some of the best tidal stream resources in the world, the potential to develop projects must be viewed in the context of the Government's Clean Growth Strategy, Industrial Strategy and the falling costs of other forms of low carbon generation, such as offshore wind. Through our policies we have massively increased our deployment of renewable generation. Renewable electricity now makes up almost 30% of our generation. Our renewable capacity has quadrupled since 2010 and the Contracts for Difference (CfD) auction prices of offshore wind have fallen from £114 per MWh to £57.50 per MWh within two years.

In the Clean Growth Strategy, which the Government published in October 2017, we underlined the need for renewable technologies to demonstrate ongoing cost reduction and to compete with other forms of low carbon generation. The strategy states that, "*More nascent technologies such as wave, tidal stream and tidal range, could also have a role in the long-term decarbonisation of the UK, but they will need to demonstrate how they can compete with other forms of generation.*" The Government will continue to consider policy related to wave and tidal stream in light of this strategy and in the context of the recent CfD allocation round. Tidal stream could still have a potentially important role in the long-term decarbonisation of the UK. It must reduce its costs sufficiently, however, to compete with other renewable technologies.

The Department is continuing to engage with wave and tidal stream developers to understand their cost-reduction trajectories, where those savings are likely to be found and, importantly in light of declining costs for other renewables, whether there may be a rationale for funding arrangements outside of the CfD.

Thank you again for taking the time to write. I hope you find this information useful.

Yours ever,

THE RT HON CLAIRE PERRY MP
Minister of State

Appendix 3 – Published papers arising from this research

During the course of this research, the author has had two papers published in Energy Policy (impact factor 4.039), and one in Utilities Policy (impact factor 2.417)

These were:

Levelised cost of energy – a theoretical justification and critical assessment, Energy Policy, 124 (2019) 169-179

Aldersey-Williams, J.; Rubert, T

Better estimates of LCOE from audited accounts – A new methodology with examples from United Kingdom offshore wind and CCGT, Energy Policy, 128 (2019) 25-35

John Aldersey-Williams, Ian.D.Broadbent and Peter.A. Strachan

Analysis of United Kingdom offshore wind farm performance using public data: Improving the evidence base for policymaking, Utilities Policy, 62 (2020)

John Aldersey-Williams, Ian D. Broadbent and Peter A. Strachan

ALDERSEY-WILLIAMS, J. and RUBERT, T. 2019. Levelised cost of energy: a theoretical justification and critical assessment. Energy policy [online], 124, pages 169-179. Available from: https://doi.org/10.1016/j.enpol.2018.10.004

Levelised cost of energy: a theoretical justification and critical assessment.

ALDERSEY-WILLIAMS, J. and RUBERT, T.

2019

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Levelised cost of energy – A theoretical justification and critical assessment

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ABSTRACT

Although widely accepted as a measure of the comparative lifetime costs of electricity generation alternatives, levelised cost of energy (LCOE) lacks a theoretical foundation in the academic literature and encompasses a number of areas where caution is important. Therefore, this paper seeks to provide a theoretical foundation by comparing the metric with alternative cost of energy metrics and by undertaking a brief literature review to describe its strengths and weaknesses. In comparison with other potential measures of unit cost of energy, LCOE is found to be the preferred choice, in large part because of its widespread adoption. The weaknesses of the LCOE are found to centre on discount rate, inflation effects and the sensitivity of results to uncertainty in future commodity costs. These weaknesses are explored in the context of comparing combined cycle gas fired generation and offshore wind in the UK, based on publicly available cost measures. It is found that with variability of future fuel gas prices, and a Monte Carlo approach to modelling LCOE, the range of LCOE for CCGT is much broader in comparison to the LCOE of offshore wind. It is urged that explicit account be taken of the areas of weakness in future use of LCOE.

1. Introduction

Levelised cost of energy (LCOE) is widely used as a comparative measure between alternative sources of energy. It is relied on by Governments (HM Government Department for Business, 2016) and Inter-Government agencies (OECD/IEA, 2015) for evaluating policy decisions in relation to differential support between carbon-based and renewable electricity generation. Data on LCOE is produced by a range of highly reputable non-government commentators such as Lazard (2016), Mott McDonald (2010), Arup (2016), and Ernst and Young (2012) as well as by academics (Astariz et al., 2015; Allan et al., 2011; Myhr et al., 2014; Ouyang and Lin, 2014). Over recent years, the difference between costs of thermal (e.g. combined cycle gas turbine, also known as CCGT) and renewable (e.g. offshore wind) power generation has fallen very considerably, as a result of technological and commercial innovation and changes in revenue support mechanisms enabling lower cost project financing. The decline in wind costs is expected to continue (Williams et al., 2017), making the importance of comparative metrics and their appropriate application ever more important.

As an influential comparative metric, it is important that the use of LCOE and the results it delivers are clearly understood. Therefore, this paper addresses a long-standing gap in the academic literature by providing a theoretical footing for use of LCOE as a comparative measure of the cost of energy. It goes on to apply the metric by taking into account identified key factors which have not necessarily been appropriately applied in the past. Following, the analysis explores the impact of varying discount and inflation rates and applies a probabilistic approach to understand the range of possible LCOE. It is found that these refinements to the application of LCOE show that offshore wind may already be cost competitive with CCGT. Partridge has recently suggested a scenario-based approach to the application of LCOE (Partridge, 2018) and has found cases where wind energy is cheaper than thermal alternatives. This paper adopts a Monte Carlo approach to explore the same question.

This paper is divided into eight sections. Section 2 reviews the literature on the definition and use of LCOE and provides a theoretical footing for one formulation of the metric. Section 3 proposes several possible alternative lifetime cost of energy metrics while Section 4 identifies the strengths and weaknesses of LCOE against these alternatives. Section 5 details the input data used in this review and Section 6 sets out the results obtained in this analysis. Finally, Section 7 discusses the results and their implications followed by a conclusion in Section 8.

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2. Overview of LCOE approaches

The calculation of the unit cost of energy can provide a useful comparative measure between projects and technologies. However, it is important that users take a consistent approach to the costs included within any calculation, and that the implicit weaknesses of any such calculation are taken into account.

The LCOE metric provides an indication of the unit energy cost over the full life of a project, including capital, operating and financing costs. In general terms, the metric sums the lifetime costs of the energy system under consideration (such as a wind farm, or CCGT power plant), and divides by the lifetime energy production to deliver an output in cost per unit energy. Conventionally, LCOE includes only "plant-level costs" (OECD/IEA, 2015) and does not take account of "effects at the system level in the sense that specific technologies demand additional investments in transmission and distribution grids or demand specific additional reconfigurations of the electricity systems" (OECD/IEA, 2015).

Two main methods for calculating LCOE are in use; one suggested by the Department for Business, Energy and Industrial Strategy (BEIS) and one suggested by the Department of Energy's National Renewable Energy Laboratory (NREL). Both methodologies are presented in depth in Sections 2.1 and 2.2, respectively.

2.1. LCOE (Department for Business, Energy & Industrial Strategy definition)

The definition for the LCOE metric which dominates in the UK defines levelised cost of energy as "the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWh" (HM Government Department for Business, 2016). The UK Government department which first produced information on LCOE was the Department of Energy and Climate Change (DECC). In 2016, DECC was merged into the Department for Business, Innovation and Skills to form a new department for Business, Energy and Industrial Strategy. The formula for LCOE used by BEIS is set out in Eq. (1):

$$LCOE_{BEIS} = \frac{NPV_{Costs}}{NPE} = \sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t} \Big/ \sum_{t=1}^{n} \frac{E_t}{(1+d)^t} \tag{1}$$

where t is the period ranging from year 1 to year n, C_t the capital cost in period t (including decommissioning), O_t the fixed operating cost in period t, V_t the variable operating cost in period t (including fuel cost, carbon costs, and sometimes taxes, etc.), E_t the energy generated in period t, d the discount rate, and n the final year of operation. As defined in Eq. (1), this method takes account of costs over the life of a project, and thereby derives a lifetime cost of energy. To the best knowledge of the authors, there is no published theoretical justification for the $LCOE_{BEIS}$ methodology found in the literature. For completion, the derivation is as follows.

$LCOE_{BEIS}$ divides the discounted sum of costs by the discounted sum of energy production. For convenience, the discounted sum of energy generated can be defined as net present energy (NPE) as illustrated in the denominator of Eq. (1). By definition, when the NPV of a project is zero, the project's internal rate of return (IRR) equals its discount rate (Brealey et al., 2006). In equation form:

$$NPV_{project} = NPV_{revenues} - NPV_{costs} = 0. \tag{2}$$

When the project IRR is equal to the discount rate ($NPV_{costs} = NPV_{revenues}$), it is possible to substitute NPV_{costs} with $NPV_{revenues}$ and thus derive Eq. (3):

$$LCOE = \frac{NPV_{revenues}}{NPE}. \tag{3}$$

As this result is expressed in terms of revenue per unit energy figure, it is natural to interpret this figure as an energy price. As the analysis above shows, the $LCOE_{BEIS}$ result is equal to the constant energy price in real terms required for the revenues generated from the project to be sufficient to return the IRR for the project equal to the discount rate.

Although BEIS states that LCOE "should not be seen as a guide to potential future strike prices" (HM Government Department for Business, 2016), it is in fact apparent that the $LCOE_{BEIS}$ does reflect a minimum required real price for a project.

The foregoing analysis is based on the costs in the model being expressed in real terms. A parallel analysis finds that if nominal costs with constant inflation factors are used as inputs, and the discount rate scaled up by the nominal inflation rate, the formula returns the average through-life nominal price required for the project to achieve an IRR equal to the nominal discount rate. When used with real costs, the metric returns a value which equates to the minimum constant real price required for a project to achieve a target return. When using nominal figures, and a nominal discount rate, the formula returns the average nominal price required through the project's life to generate the required nominal return. $LCOE_{BEIS}$ therefore has a clear, theoretically justified, and commercially-useful meaning.

2.2. LCOE (National Renewable Energy Laboratory definition)

In contrast, the US Department of Energy's National Renewable Energy Laboratory defines LCOE in terms of the annual cost of energy, where the capital costs include an annuity-based capital recovery factor (CRF) which addresses the costs of financing the capital for the project (National Renewable Energy Laboratory, 2018). Eq. (4) sets out the NREL definition for the simple levelised cost of energy, which it refers to as sLCOE and we call $LCOE_{NREL}$ (to differentiate it from the BEIS metric).

$$sLCOE = \quad LCOE_{NREL} = \frac{C_o{*}CRF + O}{8760{*}CF} + f{*}h + V \tag{4}$$

where Co is the overnight capital cost, O the fixed operating cost, CF the capacity factor, f the fuel cost, h the heat rate, and V the variable operation cost. Eq. (5) sets out the calculation of the capital recovery factor:

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{5}$$

where i is the interest rate, and n is the number of payments made to repay capital.

As such, NREL calculates total costs over an annual period and divides by the energy generated in the same period. Capital costs are expressed in terms of cost per kW installed, and modified by a capital recovery factor which calculates the equivalent annuity payment required to service the overnight capital over the term of the project's financing, and operating costs are expressed in terms of cost per kWh. NREL has published a more detailed formula for LCOE (Mone et al., 2015), allowing for more detailed analysis of costs. Both NREL formulae employ the same annualised basis for LCOE calculation, so the review in this paper applies equally to both.

NREL states that the LCOE returned by its formula is "the minimum price at which energy must be sold for an energy project to break even" (National Renewable Energy Laboratory, 2018). Put more clearly, the $LCOE_{NREL}$ is the energy price required for a project to exactly meet its operating costs in a year and the share of capital costs (including the costs of financing those costs) in that year.

Similarly, the BEIS-defined LCOE returns the constant real energy price required to generate the return equal to the discount rate used over the full life of the project.

It is worth noting that under certain simplifying assumptions, the BEIS and NREL metrics return exactly the same value. These simplifying assumptions are that the project has constant annual output and costs, that all construction spending occurs in year 1 and capital recovery starts immediately with a financing term equal to the project's operating life, and finally that there are no decommissioning costs. These requirements could be met in the case of a very simple project, such as a single wind turbine or small wind farm.

In conventional discounted cashflow-based investment appraisal, it is usual to apply discount factors to all revenues and costs, and the $LCOE_{BEIS}$ does this, making it more consistent with this approach.

Foster's thorough review of the details of alternative formulae (Foster et al., 2014) focusses mainly on which costs are included or excluded in various applications of the LCOE approach. While this is, of course important, the review in this paper focusses rather on the mechanics of the mathematical formulae in use, and what the results of these formulae mean in terms of required energy price. Neither BEIS's nor NREL's methodology is “right”, and both give an insight into the relative costs of energy, but their different characteristics mean that users must be consistent and thoughtful in which formula is selected. As this research is centred on the UK energy system, the BEIS approach has been adopted for further review.

3. Review of alternative metrics

In comparing alternative electricity generation technologies, it is useful to have a metric which indicates the lifetime unit cost of electricity generated. The $LCOE_{BEIS}$ has emerged as the standard measure in the UK, but it is only one of a family of potential measures of lifetime cost. Hence, this section compares the $LCOE_{BEIS}$ with other potential metrics in the “cost of energy” family; all of which take a total of costs and divide by the total energy generated. Two metrics are well established and are in wide usage - $LCOE_{BEIS}$ and $LCOE_{NREL}$ – and these were reviewed in Section 2.

In all of these metrics, it is critical to ensure that clear definitions of costs to be included and excluded have been made, and where discounting is applied, to have made informed choices about discount rates in the context of the cost of capital and project risk (OECD/IEA, 2015).

Three additional cost of energy metrics have been identified and defined. These are not, to the best of our knowledge, seen in the literature but offer alternative features to the LCOE metrics. They are undiscounted cost of energy (UCOE), discounted costs cost of energy (DCCOE), and total cost of energy (TCOE).

3.1. Undiscounted cost of energy

UCOE is simply the total capital and operational costs divided by the energy produced, as in Eq. (6).

$$UCOE = \frac{\sum_{t=1}^{n} C_t + O_t + V_t}{\sum_{t=1}^{n} E_t} \tag{6}$$

The UCOE measure provides a simple cost per unit energy measure, but offers no insight into the impact on value of the timing of cashflows or energy production. Whilst it might be informative in comparing projects with the same technology, it is not useful as a tool for comparison between technology types.

3.2. Discounted costs cost of energy

A possible new metric, discounted costs cost of energy, is defined by dividing the discounted sum of operational and capital costs by the sum of energy produced. It is defined in Eq. (7).

$$DCCOE = \sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t} / \sum_{t=1}^{n} E_t \tag{7}$$

DCCOE is comparable to the net present cost per barrel measure commonly used in the oil industry (Brealey et al., 2006), which also discounts the financial side of the equation but not the energy side. We believe that this measure was adopted as NPV is routinely determined in investment appraisal in the oil and gas industry, and it is a natural ranking approach to divide by the volumes of hydrocarbons relating to that NPV.

As the energy generation from all technologies is broadly constant year on year, the ratio of LCOE to DCCOE is expected to be broadly constant for each technology. Nevertheless, longer term projects will return a lower DCCOE than LCOE, as the late years production is not heavily discounted. Unlike the LCOE metric, which returns the minimum constant energy price, in real terms, required to deliver the return implicit in the discount rate, the DCCOE returns a figure which does not clearly relate to a price required for a project and this lack of apparent meaning makes it less useful as a metric.

3.3. Total cost of energy

Another new metric, total cost of energy is defined as the total project cost, including financing costs divided by the energy produced, as presented in Eq. (8).

$$TCOE = \frac{\sum_{t=1}^{n} C_t + O_t + V_t + F_t}{\sum_{t=1}^{n} E_t}. \tag{8}$$

The costs of financing incurred during each year, *Ft*, are calculated on an annuity formula, which assumes capital costs are financed on an annuity basis over a defined lifetime. Operating costs in the project are assumed to be paid from annual revenues and therefore do not incur financing costs. While this treatment of operating costs reflects the operating reality for most projects, it means that the TCOE metric is not consistent with conventional investment appraisal, in which all costs are discounted.

Eq. (8) returns a figure which describes the lifetime cost of energy, and, like $LCOE_{BEIS}$, includes financing costs, and it is worth exploring how its results differ from $LCOE_{BEIS}$.

TCOE is closely related to the $LCOE_{NREL}$ definition, as both build in the costs of a financial return with an annuity formula and only expect a return on the capital costs. They differ in that TCOE considers costs over the full project life, allowing for inter-year variability in costs, while $LCOE_{NREL}$ considers costs on an annual basis.

3.4. Summary of findings

Fig. 1 shows the breakdown of costs between technologies as presented by BEIS (HM Government Department for Business, 2016). It is clear that offshore wind is dominated by construction costs, while thermal projects, such as CCGT are dominated by fuel and variable operating costs.

A simplified Excel® model has been constructed to compare the results returned by each metric for notional CCGT and wind projects. The input data has been developed to ensure that the notional CCGT and wind projects return the same $LCOE_{BEIS}$. Fig. 2 shows the results.

TCOE returns the highest values, as it includes all costs (undiscounted) and divides by discounted energy. Conversely, DCCOE, which discounts costs but not energy, returns the lowest value for both technology families. ULCOE, which divides undiscounted capital and operating costs by undiscounted energy strongly differentiates between thermal and wind projects, as the different timing profiles and amounts of capital and operating spend is affected differently by the removal of discounting. The costs of thermal projects, with their long high operating cost profiles, are more reduced by the discounting process than those of wind projects, whose costs are much more front-end biased.

Focussing on the LCOE measures, it is found that $LCOE_{BEIS}$ and $LCOE_{NREL}$ are broadly similar for the two technology families. In the case shown in Fig. 2, in which the Capital Recovery Factor is applied over the full operational life of 25 years, $LCOE_{NREL}$ is some 12% lower than $LCOE_{BEIS}$; if capital recovery is accelerated to a 15 year period, $LCOE_{NREL}$ is higher than $LCOE_{BEIS}$ by a similar factor. In the case of thermal projects, the $LCOE_{NREL}$ is less variable, as the lower fraction of

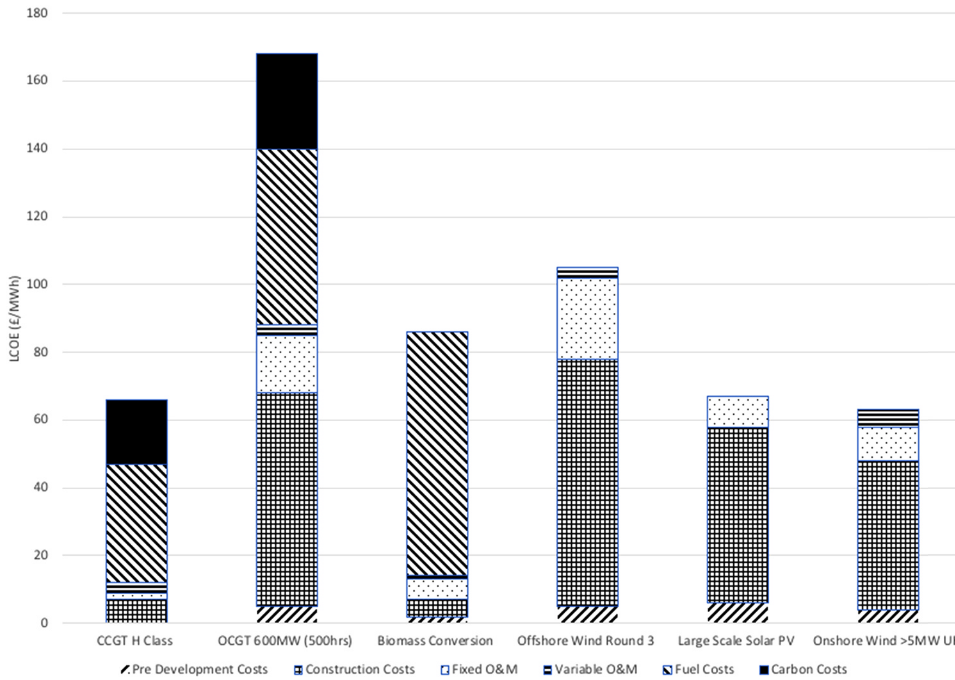

Fig. 1. Breakdown of levelised costs across technologies, data from (HM Government Department for Business, 2016).

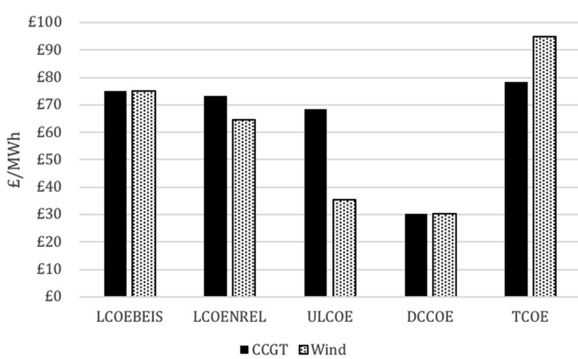

Fig. 2. Comparison of unit cost of energy metrics (authors' analysis).

costs attributable to capital make the sensitivity to CRF less.

Each metric's key features, their outcome and benefits as well as drawbacks are further summarised in Table 1.

The key strength of $LCOE_{BEIS}$ is that it generates a figure equal to the constant real energy price required by a project to return the rate of return on capital invested equivalent to the discount rate used in the formula, and therefore equivalent to the energy price required by the project in an inflation-free world.

3.5. Other measures

Other authors have recently proposed the extension of LCOE to provide additional information. These proposals include accounting for the costs of externalities (such as environmental damage, health and mortality effects) when comparing between technologies (Millstein et al., 2017); including the costs of carbon taxes or other carbon costs (Aquila et al., 2017); and seeking to evaluate the relative contribution to a local or national economy by considering the fraction of spend which contributes to local or national gross value added (GVA) (Roberts, 2017). All of these are interesting and relevant proposals, as the comparison of electricity generation technologies should take account of these wider factors, but they are not considered to be within the scope of this paper.

4. Strengths and weaknesses of LCOE relative to other cost of energy metrics

All measures of unit cost of energy must be considered as simple "rules of thumb" and are exposed to weaknesses relating to the choice of costs included and excluded. This review recognises that tax effects may impact calculations of unit cost of energy, particularly where targeted preferential tax treatment regimes are in place (for example in the United States where production tax credits may apply to renewable energy (US Department of Energy, 2018)), but has not explicitly addressed these. Wider costs, including environmental and other externalities might also legitimately affect choices between technologies, but these have also not been addressed in this paper.

4.1. Strengths

$LCOE_{BEIS}$ has been widely discussed in the literature (Astariz et al., 2015; Kammen and Pacca, 2004; Manzhos, 2013; Sklar-Chik et al., 2016) but the principal focus has been on the application of the metric, its weaknesses and potential improvements. A discussion of the strengths of the metric is long overdue, not least because of its widespread use and acceptance. The principal strengths of the $LCOE_{BEIS}$ metric are simplicity, sophistication, interpretation, and adoption.

$LCOE_{BEIS}$ reduces complex comparisons to a single number. This simplicity necessarily disregards some subtleties, even where these can lead to inappropriate conclusions in some cases. However, this simplicity offers the advantage of reducing a comparison to a single number, providing ease in explaining policy choices to an inexperienced public. By definition, all of the LCOE metrics proposed here share the strength of distilling a comparison into a single number.

The $LCOE_{BEIS}$ metric's sophistication allows it to take some account of capital and operating costs, operational performance and costs of finance in assessing a cost of energy. The metric therefore has a degree of sophistication, which helps to justify its use as a high level comparative tool. Other LCOE metrics, as proposed here, do not offer the same sophistication in fully considering intra-year variability in costs (particularly fuel costs) or costs of project financing.

$LCOE_{BEIS}$ is only one of a family of possible lifetime cost of energy calculations, each of which can claim to being a valid tool for cross-

Table 1
Comparison of lifecycle cost alternatives (authors' analysis).

Parameter	$LCOE_{BEIS}$	UCOE	DCCOE	TCOE	$LCOE_{NREL}$
Key features	Discounted total costs (excluding finance costs) divided by discounted total energy	Simple sum of costs (excluding finance costs) divided by simple sum of energy	Discounted total costs (excluding finance costs) divided by simple sum of energy	Total undiscounted costs including finance costs divided by total energy	Annual costs (including financing costs for capital) divided by annual energy
Outcome and meaning	Constant real price required to generate IRR equal to discount rate	Constant real price required for total costs to equal total revenue (i.e. zero return)	Net present cost per unit energy Informs on required net present value of revenue stream for project return	Average flat real price required to cover all costs and generate return on capital	Annual price required to cover operating costs and service finance costs
Benefits	Widely used in UK Returns meaningful metric equivalent to minimum economic price	Simple to calculate Easily understood	Net Present Cost per unit energy is clearly understood Indicates net present value required from revenue stream for return	Closely related to $LCOE_{NREL}$ but can include costs of financing operating costs	Widely used in US
Drawbacks	Sensitive to discount rate	Does not reflect time value of money; not in wide use	Difficult to explain; not in wide use	Not consistent with conventional project appraisal; not in wide use	Unable to address annual variable costs (e.g. fuel costs); not consistent with conventional project appraisal; does not take into account return of investment and time value of cash flows

technology comparison. It is in relation to meaning that $LCOE_{BEIS}$ has a critical advantage, and Section 2 of this paper sets out a theoretical backing for the preference of $LCOE_{BEIS}$ over other measures, by considering the meaning of the results returned by the methodology.

Notwithstanding the new theoretical justification offered here, perhaps the most compelling benefit of the $LCOE_{BEIS}$ metric is its wide adoption. It is used by BEIS (HM Government Department for Business, 2016) as a comparative tool, and employed by a range of commentators (Lazard, 2016; Mott McDonald, 2010; Arup, 2016; Ernst and Young, 2012) in considering the merits of renewable energy as compared with conventional thermal generation.

4.2. Weaknesses

A number of authors, including academic researchers (Manzhos, 2013; Sklar-Chik et al., 2016; Cartelle Barros et al., 2016) and other writers (Bronski, 2014; Bolton, 2016; Irons, 2016) interested in the comparative costs of energy sources have discussed the weaknesses of the LCOE metric. Memorably, Cartelle Barros described LCOE as “an abstraction from reality” (Cartelle Barros et al., 2016) but accepted that it is “used as a benchmarking or ranking tool to assess the cost-effectiveness of various energy generation technologies”. Joskow expanded on this, pointing out that LCOE does not consider the impact of changes in the value of electricity through the day, or the difference in value between dispatchable and intermittent generation (Joskow, 2011). More recently, Laszlo Varro, the Chief Economist for the International Energy Agency (IEA), said that LCOE was becoming less relevant as a metric, as it failed to take into account wider system costs or to deal with variability and intermittency (Snieckus, 2017). This paper does not address the concerns relating to intermittency and wider system integration, but focusses on the weaknesses identified by Manzhos, Sklar-Chik et al., Cartelle Barros et al. and others (Manzhos, 2013; Sklar-Chik et al., 2016; Cartelle Barros et al., 2016) which are concentrated in three detailed areas: (i) discount rates, (ii) treatment of inflation, and (iii) dealing with uncertainty in future costs.

Choice of an appropriate discount rate has long been contentious in many areas of financial analysis (Frederick et al., 2002; Henderson and Bateman, 1995; Weitzman, 1998), and this is also true in the LCOE literature (Manzhos, 2013). As (Manzhos, 2013) points out, the choice of discount rate has a significant effect on the LCOE. He goes on to argue that the most appropriate rate to use in comparing technologies is the risk-free rate. In practice, different discount rates may be used for different technologies, in an attempt to account for different risk profiles (HM Government Department for Business, 2016). BEIS uses a “hurdle rate” which it defines as “the minimum project return that a plant owner would require over a project's lifetime on a pre-tax real basis” and is set to “reflect different financing costs for different technologies”. These rates therefore reflect the weighted average cost of capital (WACC). This has the effect of raising the LCOE for technologies considered to be riskier, and potentially skews the metric in favour of apparently less risky technologies. As the discount rate reflects the project risk, it is also important to recognise that the appropriate discount rate to be applied can change through a project's life. Increasingly financial investors such as pension and insurance companies are investing in offshore wind projects. These companies generally have lower return expectations and appetites for risk than developers, and this trend is indicative of the perceived reduction in project risk as this technology matures. Section 6 explores the effect on $LCOE_{BEIS}$ of variations in discount rate.

The second key weakness in application of the LCOE metric is in the handling of inflation. Sklar-Chik et al. (2016) has said that the conventional application of the $LCOE_{BEIS}$ metric does not take into account cost inflation, and says that “it is possible to account for inflation, although this requires somewhat more intensive calculation”. In this work, it has been found that the $LCOE_{BEIS}$ formula readily accommodates nominal costs (i.e. costs with inflation), as long as nominal

Table 2
Input data for deterministic assessment (HM Government Department for Business (2016) and authors' analysis).

Input parameter	CCGT	Unmodified Wind farm	Scaled wind farm
Capacity (MW)	1200	844	844
Availability / Capacity Factor (%)	93%	48%	48%
Prebuild costs (£/kW)	10	120	74
Construction (£/kW)	500	2300	1409
Infrastructure (£'000 s)	15,100	323,000	197,870
Fixed O&M (£/MW/yr)	12,200	47,300	28,976
Variable O&M (£/MWh/yr)	3	3	2
Fuel cost conversion factor (%) (converts fuel cost (p/therm) to annual variable cost (£/MWh)	110%	Zero fuel cost	Zero fuel cost
Insurance (£/MW/yr)	2100	3300	2022
Connection charges (£/MW/yr)	3300	48,900	29,956
Discount rate (%)	7.8%	8.9%	8.9%
Operating life (yrs)	25	25	25
LCOE (£/MWh)	47.00	103.88	57.50

discount rates are used, and it is understood that the result is an average nominal energy price required over the life of the project to deliver the nominal discount rate. Inflation is explicitly built into strike prices under UK contracts for difference (CfD) of renewable energy auctions (Low Carbon Contracts Company, 2018), making this aspect of the analysis relevant and important. The incorporation of inflation can generate divergent results between different technologies, as a result of their different temporal patterns of expenditure. This difference means that as cost inflation increases, the proportionate increase in $LCOE_{BEIS}$ for CCGT projects is greater than for offshore wind. This is explored further in Section 6.

This could have significant effects when the $LCOE_{BEIS}$ metric is used to compare between thermal and renewable technologies. Over a full life cycle, the costs of CCGT plants are dominated by operating and fuel costs, as shown in Fig. 1, while offshore wind costs are dominated by the capital costs, which are less susceptible to the effects of inflation, as they take place over a limited period (and can potentially be limited by contractual arrangements). While constant inflation, where nominal prices increase by a constant percentage each year, can be accommodated within the $LCOE_{BEIS}$ formula without stress, experience suggests that it is unreasonable to expect fuel gas prices to behave in this manner. This is further explored below.

The largest element of costs in a CCGT project is fuel costs. Conventionally in calculating $LCOE_{BEIS}$, a deterministic forecast of gas prices is employed to determine the "most likely" future costs (HM Government Department for Business, 2016). The BEIS report (HM Government Department for Business, 2016) includes some sensitivity analysis to examine the effect on LCOE of uncertainty in future gas prices, but this is relegated to a separate chart and does not form a key part of the conclusions. Over the past two decades, wholesale gas prices have varied widely, and it is not obvious why similar volatility should not be expected in the future. Probabilistic analysis, as pioneered in the calculation of LCOE by Cartelle Barros et al. (2016), Heck et al. (2016) offers an appropriate tool to understand the variability of LCOE for CCGT projects. Neither of these authors considered offshore wind in their analysis, and recent significant reductions in costs for this technology make this timely and important.

In summary, the $LCOE_{BEIS}$ metric is considered to be the most informative metric as to comparative economics of energy generation alternatives, as it generates the constant price in real terms required for the project to generate the return indicated by the discount rate and it is already in widespread use. Other measures, whilst informative in different ways, suffer from a lack of widespread adoption and/or a lack of apparent "meaning" to the results they return in terms of real world applicability. For these reasons, this paper now focusses on $LCOE_{BEIS}$ in considering the effect of variation in key input parameters.

Sections 5 and 6 explore the quantitative effects on $LCOE_{BEIS}$ of variation in each of these factors (discount rate, inflation and cost uncertainty) in turn and in combination, to evaluate realistic and current estimates for $LCOE_{BEIS}$ for CCGT and offshore wind.

5. Method and input data

A detailed Excel® model has been built to determine LCOE for an idealized CCGT project and an idealized offshore wind project. Costs have been taken from BEIS' report of UK electricity generation costs (HM Government Department for Business, 2016).

5.1. Deterministic method

In the case of CCGT, converting from wholesale gas price in pence per therm (1 therm = 1.0 MMBTU = 29.3 kWh) to annual fuel costs requires a conversion factor which has been used to ensure that the LCOE generated in our analysis for CCGT equates to £47/MWh. This ties the model outputs into the BEIS report, which states that the central case LCOE for CCGT is £66/MWh including carbon taxes of £19/MWh (HM Government Department for Business, 2016).

Costs for offshore wind have also been taken from the BEIS report (HM Government Department for Business, 2016). Based on the central case costs in the BEIS report, the LCOE is calculated as £103.88/MWh. In order to reflect currently anticipated changes in offshore wind costs, costs have been reduced by a scaling factor to produce a base case LCOE at £57.50/MWh (the initial strike price to be received under the recently-announced second round CfD). The implementation of the scaling factor is illustrated in Table 2.

It is recognised that LCOE and strike price do not necessarily equate, but as LCOE is a constant real price required to offer the required return (implied by the discount rate used) it is an appropriate starting point for this comparative analysis. In practice, since there is guaranteed inflation linkage in the strike price under the CfD arrangements (Low Carbon Contracts Company, 2018), the contractual price, and its built-in inflation factor, will likely generate higher revenues and therefore a return above the discount rate used by BEIS to calculate LCOE.

5.2. Deterministic input data

The input data used for the deterministic assessment is set out in Table 2. The BEIS analysis (HM Government Department for Business, 2016) includes carbon taxes in thermal generation costs. This analysis has ignored the potential effect of carbon taxes, as it is interested to see whether offshore wind costs, based on recent CfD auctions, are now legitimately competitive with CCGT.

With the model calibrated, it was then used to vary discount rates, inflation rates and to determine $LCOE_{BEIS}$ under each of these cases.

5.3. Probabilistic method and input data

The Monte Carlo method allows key variables in a calculation to vary within defined probability distributions over multiple calculation iterations to generate multiple outcomes which define the range of possible outcomes for the target metrics. A statistical analysis of this range is undertaken, to allow users to understand the likely range of outcomes, in terms of the median outcome (the "P50", or the value for which there is a 50% probability of exceedance) and the likely extremities of the range, which are typically presented as "P10" and "P90" values. There is a 90% chance of the LCOE being higher than the P90 value, and a 10% chance that it exceeds the P10.

For both offshore wind and CCGT, it has been assumed that capital and operating costs derived from BEIS' central cases (HM Government Department for Business, 2016) are varied within a distribution with bounds at ± 10% of the central case. While offshore wind technology is arguably less developed than CCGT, in practice operators ensure that their costs are very tightly constrained before bidding projects into the CfD process and proceeding to final investment decision, so similar ranges for these technologies are appropriate.

Fuel costs for CCGT are likely to be more variable, and have been modelled in two different ways. BEIS (HM Government, Department for Business, 2016.) provides a range of price forecasts from the present until 2035. In the first analysis, these have been used as the basis for future fuel gas prices, and to model variability, the selected gas price in any year has been selected randomly with equal probabilities between the central, high and low price cases. The second analysis adopts an approach in which future gas prices are based on a statistical review of past gas prices, on the basis that future volatility may be similar to that shown in the past. The fuel price for 2017 is taken from the BEIS central case forecast (HM Government, Department for Business, 2016.). The fuel gas price for each subsequent year is then derived from the previous year, with a percentage change derived from the statistical distribution of annual price change defined by past UK gas prices from the BP statistical review of world energy 2017 (BP Plc, 2017). These data points cover two decades, from 1996 to 2016. An analysis of this data shows that the mean annual change in gas price was 10.7% and the standard deviation 36.8%, meaning that the 95% confidence interval for annual gas price change was −62.9% to +84.3%. This is considerably more variability than in the BEIS forecasts, and consequently it generates a much wider range of LCOE outcomes for the CCGT case. The recent variability of gas prices seems to be the more reasonable basis on which to model future variability, as it builds forecasts which respect the largely random price variability seen in the past.

Finally, capacity factors for offshore wind farms have been allowed to vary within a normal distribution, with a mean of 48% and standard deviation of 3%, based on our own analysis (in press).

The spreadsheet model employs Visual Basic to generate multiple outcomes, sampling the variability of operating costs, capital cost, fuel costs and wind farm output within the ranges defined. In this analysis, it was found that 20,000 iterations were sufficient to develop robust distributions of solutions. The input data used for the probabilistic assessment is set out in Table 3.

6. Results and commentary

6.1. Discount rate

BEIS applies a discount rate of 8.9% for offshore wind projects and 7.8% for CCGT projects (HM Government Department for Business, 2016); this is in agreement with the range for cost of capital recently estimated by the Competition and Markets Authority for integrated generation companies (Competition and Markets Authority, 2015).

With the introduction of CfDs for offshore wind (Onifade, 2016), the revenue risk for offshore wind has been drastically reduced. Revenue is the product of output and price, and with the constant price (guaranteed by a zero-risk Government-backed contract), the effect of CfDs is to remove a key revenue risk factor. Accordingly, as the revenue risk is much reduced, the projects can employ much higher levels of project finance than previous offshore wind projects at historically low rates, allowing operators to maintain equity returns at a lower WACC. It would therefore be appropriate to consider lower discount rates in considering LCOE for post-commissioning projects, and to undertake sensitivity work in assessing project LCOE.

It is reported (Chalons-Browne, 2015) that there is growing competition among lenders for early CfD projects, suggesting that debt returns will be very low, particularly as interest rates at the time of project financing were generally low. Linklaters, a law firm, recently announced that the Beatrice offshore wind farm has secured nearly 75% project finance (£1.9 billion debt on a £2.6 billion project) (Offshorewind.biz, 2016), and a number of recent reports on offshore wind financing indicate that 15 year project finance is currently priced at 250–300 basis points over base rates (Wind Europe, 2018; European Wind Energy Association, 2013), for a total debt rate of around 3.5–4% and gearing levels in excess of 70%. These reports suggest that developers and investors are using variable rate debt, although there may be conversion to fixed rate debt at a later date to protect lender returns. The equity return implied from the BEIS hurdle rate of 8.9% can be calculated from the WACC formula in Eq. (9).

$$\text{WACC} = r_{equity}.\,(1 - w_{debt}) + r_{debt}.\,w_{debt} \tag{9}$$

where r_{equity} and r_{debt} are the returns on equity and debt respectively, and w_{debt} is the percentage of debt in the capital base.

Substituting WACC = 8.90%, r_{debt} = 3.5%, w_{debt} = 70% allows calculation of the implied equity return of 21.5%. This is an extremely attractive equity return, and it would only be reduced to 17.8% if the WACC was reduced to 7.8% in line with CCGT projects.

Table 4 shows the impact of this potential change to the discount rate on $LCOE_{BEIS}$ from offshore wind projects and compares to CCGT values.

This analysis finds that if the discount rate for offshore wind is reduced to 7.8%, to match that for CCGT, the LCOE falls from £57.50/MWh to £54.11/MWh; a reduction of 6%.

It therefore appears from this analysis that if BEIS is using the discount rate as a surrogate for WACC, it should consider applying a lower discount rate to offshore wind projects. The appropriate discount rate for CCGT has not been addressed here, although the risk in CCGT projects is strongly related to gas prices, and it might be argued that a higher discount rate might be appropriate to reflect this cost risk and its associated impact on the potential scope for gearing of these projects at the same levels as offshore wind.

6.2. Inflation

The impact on $LCOE_{BEIS}$ of different inflation rates is shown in Table 5. This analysis retains the real discount rates (d_{real}) for the projects applied by BEIS. As a result, the nominal discount rates (d_{nom}) applicable at different inflation rates are calculated according to the formula in Eq. (10).

$$d_{nom} = [(1 + d_{real})*(1 + \text{inflation rate})] - 1. \tag{10}$$

Comparison across each inflation rate is valid as the discount rate includes the risk premium implicit in the BEIS analysis.

Table 3
Input parameters for probabilistic analysis (authors' analysis).

Input parameter	CCGT	Scaled wind farm
Availability variation	No data available - output fixed at 93%	Capacity factor mean 48%, standard deviation 3%
Capital cost variation	+/- 10%	+/- 10%
Fixed operating cost variation	+/- 10%	+/- 10%
Variable operating cost variation	+/- 10%	+/- 10%
Fuel cost variation	Two cases: BEIS high/central/ low cases and variation with probabilistic range	N/A

Table 4
Impact of discount rate on $LCOE_{BEIS}$ (authors' analysis).

$LCOE_{BEIS}$ at different discount rates	7.8% discount rate	8.9% discount rate
Offshore wind	£ 54.11/MWh	£ 57.50/MWh
CCGT	£ 47.00/MWh	£ 47.25/MWh

Table 5
Impact of inflation on $LCOE_{BEIS}$ (authors' analysis).

Inflation rate (%)	Nominal discount rate (%)	Wind farm LCOE £/MWh	Wind farm change relative to zero inflation	Nominal discount rate (%)	CCGT LCOE £/MWh	CCGT change relative to zero inflation
0%	8.9%	57.50	–	7.8%	47.00	–
1% pa	10.0%	64.20	11.7%	8.9%	53.01	12.8%
2% pa	11.1%	71.38	24.1%	10.0%	59.47	26.5%
5% pa	14.3%	95.86	66.7%	13.2%	81.62	73.7%

Table 5 shows that the impact of non-zero inflation on $LCOE_{BEIS}$ for CCGT projects is greater than for offshore wind projects. With each increase in inflation, the $LCOE_{BEIS}$ of CCGT projects increases by a larger factor than for offshore wind projects. Of course, in a financial project assessment, operators will make assumptions about both cost and price inflation, but only cost figures affect the LCOE, and these disproportionately impact CCGT and other thermal projects.

6.3. Uncertainty in future prices

BEIS (HM Government, Department for Business, 2016) sets out high, reference and low gas price forecasts for the period to 2035, as set out in Fig. 3.

Applying each of these cases in turn, with the gas price applied in each year derived from the BEIS data, the effect on $LCOE_{BEIS}$ for CCGT projects is set out in Table 6.

Use of the BEIS high and low gas prices cases shows that the $LCOE_{BEIS}$ from CCGT can vary within a considerable range, depending on the price of fuel. The variability critically depends on the range of fuel gas estimates, which are examined further in Section 6.5.

6.4. Combined deterministic output

Table 7 shows the nominal $LCOE_{BEIS}$ results in the case where the real discount rates for both CCGT and offshore wind projects are set at 7.8%, inflation is set at 2% and the cases are run for each of the gas price forecasts.

Recalling that the results of the nominal $LCOE_{BEIS}$ formula represent the average nominal price required to achieve a return equal to the nominal discount rate, it appears that in this deterministic analysis, the costs of offshore wind can be less than those for CCGT, if fuel gas prices are in the high case as illustrated in Fig. 3.

6.5. Probabilistic results

The sensitivity of CCGT $LCOE_{BEIS}$ to fuel gas prices suggests that a probabilistic approach would offer a richer analysis with which to compare technologies. All of the analysis has taken the same basic input data as the combined deterministic analysis above, with real discount rates at 7.8%. In addition, input parameters have been allowed to vary as defined in Table 4.

The first probabilistic analysis is based on fuel gas prices varying between the reference, low and high cases defined by BEIS. Fig. 4 shows a comparison of gas price forecasts presented by the UK Government in 2006 (HM Government, 2008), against actual gas prices which were actually experienced in the period for which the forecasts were presented. It is immediately apparent that actual prices were much more variable than the forecasts, and frequently ranged outside the minimum/maximum ranges in these forecasts.

Table 6
Impact of gas price case on CCGT $LCOE_{BEIS}$ (authors' analysis).

Gas price case	$LCOE_{BEIS}$
Reference	£ 47.00/MWh
Low case	£ 34.10/MWh
High case	£ 56.17/MWh

Table 7
$LCOE_{BEIS}$ with gas price variability and 2% inflation (authors' analysis).

Scenario	Wind farm $LCOE_{BEIS}$	CCGT $LCOE_{BEIS}$
Nominal discount rate 10.0%, inflation 2%, reference gas price	£ 67.64/MWh	£ 59.47/MWh
Nominal discount rate 10.0%, inflation 2%, low gas price	£ 67.64/MWh	£ 43.15/MWh
Nominal discount rate 10.0%, inflation 2%, high gas price	£ 67.64/MWh	£ 71.08/MWh

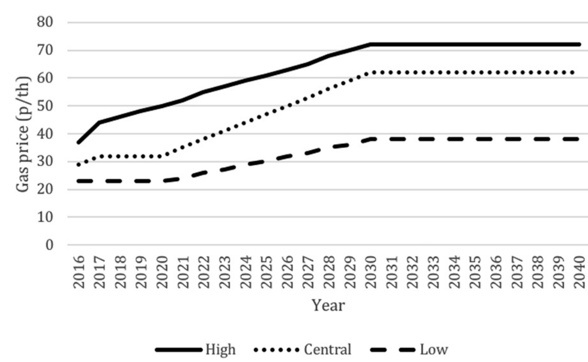

Fig. 3. BEIS gas price forecasts (HM Government, Department for Business, 2016).

Fig. 4 shows that it might be argued that short term (up to 3 year) trends can be observed in gas prices. Accordingly, the analysis allows for each three year period to apply a gas price case at random from the three BEIS gas price series.

This analysis is summarised in Fig. 5, which shows that the range of possible $LCOE_{BEIS}$ outcomes for CCGT is generally below that for offshore wind, with only minimal overlap.

Table 8 shows the analysis of these results, in which the range of values for $LCOE_{BEIS}$ for CCGT is generally below that of offshore wind across the range of probabilities. In this case, there is a 1% chance that the $LCOE_{BEIS}$ for CCGT exceeds the P50 $LCOE_{BEIS}$ for wind (the area under the CCGT graph above £54.14/MWh is c. 1%).

However, this analysis is based on the range of BEIS gas price forecasts, and if these forecasts are wrong, the range of CCGT $LCOE_{BEIS}$ values may be significantly altered. Uncertainty in CCGT availability has also not been considered.

This analysis suggests that relying on the latest BEIS price forecasts to define the possible range of future fuel gas prices is likely to underestimate the possible range of $LCOE_{BEIS}$ for CCGT projects. Accordingly, building on the premise that the past can be a guide to the future, a probabilistic analysis has been undertaken within which gas prices are allowed to vary according to a statistical analysis of their variability over the past 20 years. BP (BP Plc, 2017) provides UK National Balancing Point (NBP) price data, in \$/MMBTU. This has been

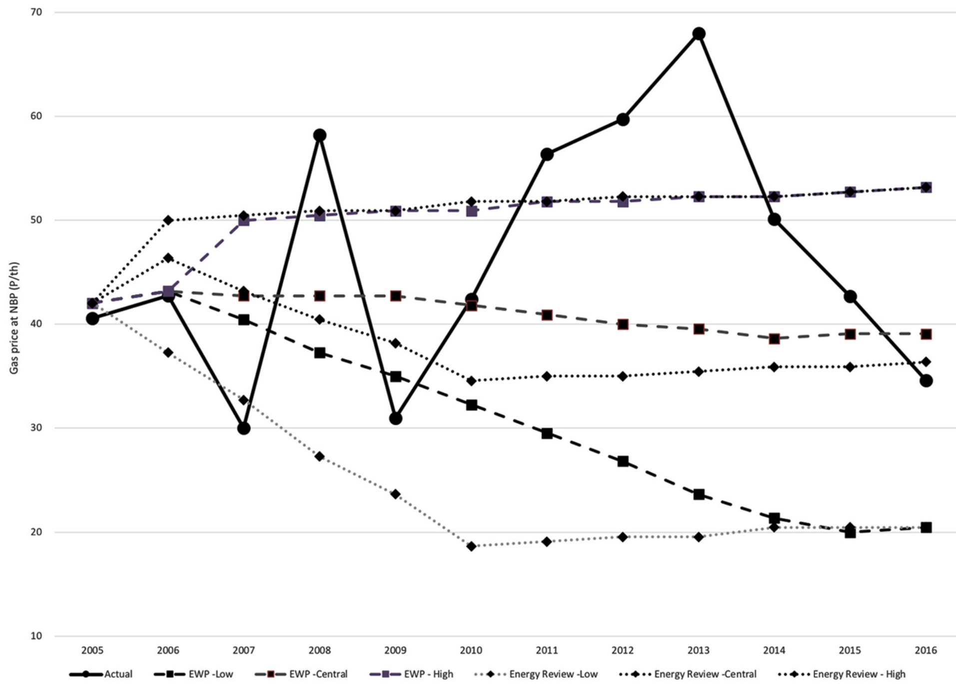

Fig. 4. Comparison of actual vs. forecast gas prices ((HM Government, 2008) and authors' analysis).

converted to UK Sterling values, and deflated by an inflation index to 2016 terms. The statistical distribution of year by year changes, in real 2016 terms, is derived.

It is found that the average (mean) change in gas price from year to year, in 2016 terms, was 0.84p/therm with a standard deviation of 14.9p/therm. Over a shorter period of a single decade, it is found that the variability is higher; the longer time series has been used as the basis for developing a statistical gas price forecast for the Monte Carlo

Table 8
Probabilistic results - BEIS gas price scenarios (authors' analysis).

Technology	P90	P50	P10
CCGT	£ 37.82/MWh	£ 45.76/MWh	£ 50.39/MWh
Offshore wind	£ 45.87/MWh	£ 54.14/MWh	£ 59.80/MWh

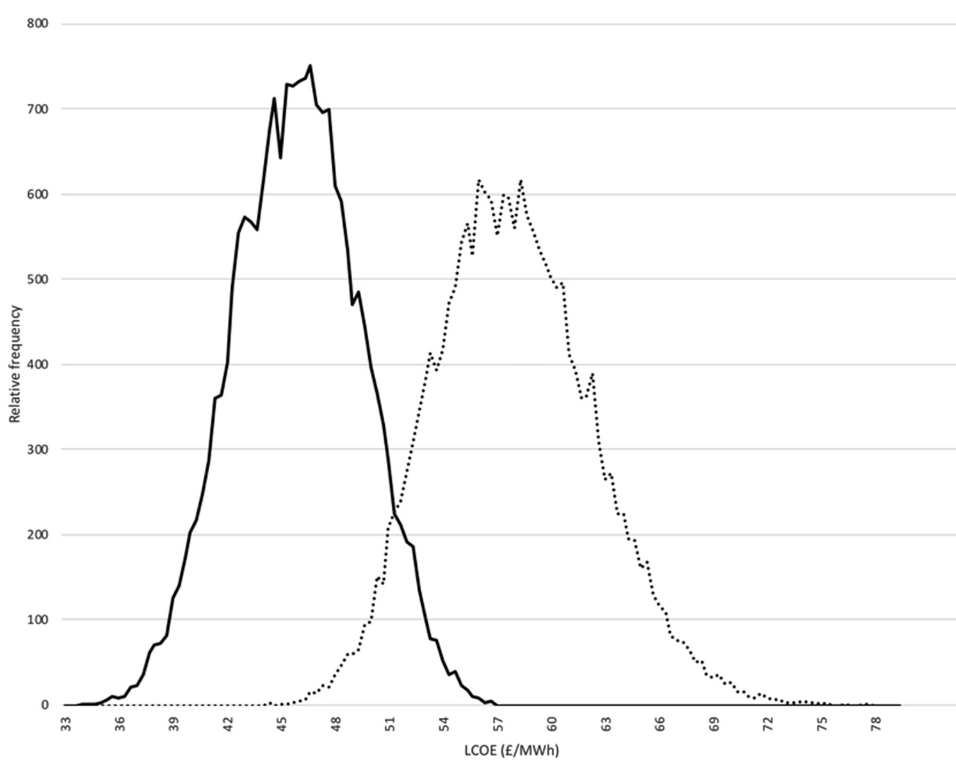

Fig. 5. $LCOE_{BEIS}$ ranges for CCGT and Offshore Wind (authors' analysis).

Table 9
Probabilistic results -statistical gas price scenarios (authors' analysis).

	P90	P50	P10
CCGT	£ 17.30/MWh	£ 45.59/MWh	£ 83.48/MWh
Offshore wind	£ 45.87/MWh	£ 54.14/MWh	£ 59.80/MWh

analysis.

The Monte Carlo model has been adjusted to allow the fuel gas price for CCGT to vary within the statistical distribution determined by past data (i.e. the change from year to year in real terms was set to have a mean of 0.84p/therm with a standard deviation of 14.9p/therm), and the initial results for this are shown in Table 9 and in Fig. 6.

This analysis shows that the range of variability of $LCOE_{BEIS}$ for CCGT is much higher than for offshore wind.

In this case, it is clear that the possible range of CCGT varies widely between around £17/MWh and £120/MWh with the median (P50) at £45/MWh, while offshore wind remains well constrained around £45–60/MWh. Under these assumptions, there is a 38% chance that the $LCOE_{BEIS}$ for CCGT exceeds the P50 $LCOE_{BEIS}$ for wind. The much wider range in possible $LCOE_{BEIS}$ for CCGT is clearly attributable to the wider range in possible fuel gas prices used in this latter analysis.

Although further statistical analysis on the variability of fuel gas prices is required, it is clear that this factor is a powerful driver of the $LCOE_{BEIS}$ for CCGT projects. By extension, it is likely that the $LCOE_{BEIS}$ for coal and oil fired generation is also likely to be strongly driven by feedstock prices.

7. Discussion

There is a considerable literature in which the LCOE metric is used. Perhaps surprisingly, it is rare to find any discussion of theoretical basis for the metric in literature, which focusses instead on its application. It is as if the metric sprang rapidly into widespread use before there was any opportunity to consider whether it was genuinely the most suitable metric to use.

Its promotion by both NREL (National Renewable Energy Laboratory, 2018) and the UK Government BEIS (HM Government Department for Business, 2016) may well have led to its widespread adoption as the "standard" measure, and its use by well-respected commercial entities such as Lazard (2016), Mott McDonald (2010), Arup (2016) and Ernst and Young (2012) are likely to have added to its perceived gravitas.

Perhaps rather late in the day, a theoretical justification for $LCOE_{BEIS}$ has been offered here and its use justified in the context of other potential measures of lifetime costs of energy. The comparative review undertaken here suggests that $LCOE_{BEIS}$, particularly when used with real (rather than nominal) costs, does provide useful insight into the minimum price required for a project to achieve a target return. As Table 1 shows, $LCOE_{BEIS}$ is merely one of a family of potential metrics to evaluate the unit cost of energy. While other metrics are available, adoption of an alternative to $LCOE_{BEIS}$ would not offer such an increase in benefits that the abandonment of $LCOE_{BEIS}$ should be recommended.

It is critical however to note that $LCOE_{BEIS}$ and $LCOE_{NREL}$ are different measures, as the BEIS measure includes an allowance for the financing requirements of operating costs, while the NREL measure does not. Users should be clear which metric they are using, and why. It is noted that both benefit from the credibility of being called LCOE, despite their differences.

Many authors use the LCOE without any explicit reference to the importance of appropriate choice of discount rates or to the impact of inflation or uncertainty in future costs, and this can give rise to misleading or even unhelpful results, as this analysis has determined.

This analysis has found that selection of appropriate discount rate, inflation rate and probabilistic modelling of future costs can radically change the perception of the relative merits of energy generation alternatives. In particular, the variability in future fuel prices for CCGT (and by extension, other thermal technologies) can significantly alter the possible range of LCOE. Fig. 6 shows that the possible range of

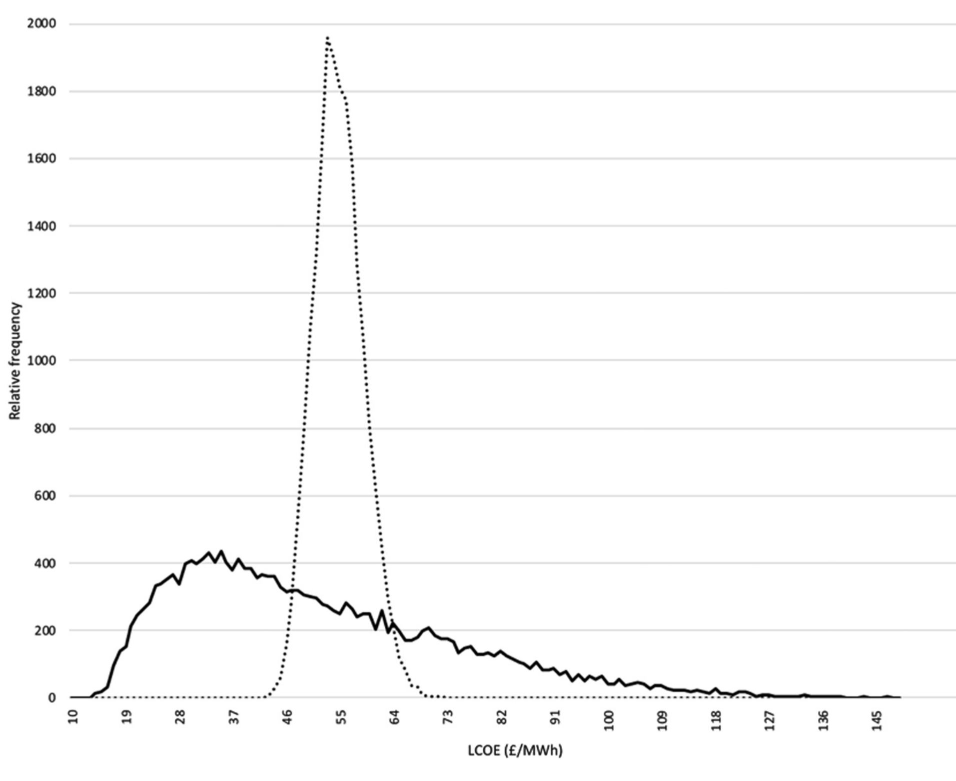

Fig. 6. $LCOE_{BEIS}$ for CCGT and Offshore wind, with statistical fuel gas prices (authors' analysis).

$LCOE_{BEIS}$ for CCGT, from £17/MWh to £120/MWh might be so great as to make the choice for offshore wind (range from £45/MWh to £60/MWh) a less risky choice. In the light of historic variability of gas prices, attempting to make meaningful deterministic forecasts of fuel prices seems doomed to inaccuracy. While scenario-based approaches might give some sense of the range of possible LCOEs, it can be hard to resist the temptation to pick a preferred scenario and rely on its deterministic result. This can lead to poor decision-making, and it is therefore strongly urged that a probabilistic approach be taken in the application of the $LCOE_{BEIS}$ metric, to provide richer information on the relative merits of alternatives.

The metric still has weaknesses: on one side, the impact on a national electricity distribution system of the intermittency of renewables, as compared with the dispatchable nature of thermal generation (explored by Joskow (2011)) is not directly addressed; conversely, application of the $LCOE_{BEIS}$ metric rarely includes any attempt to value the carbon impact of thermal technologies or other externalities. With offshore wind and CCGT technologies now apparently approaching comparability on the basis of LCOE, it may be time for application of the metric to address these sophistications.

As overall project costs for offshore wind reduce over time, and become more directly competitive with thermal electricity generation, it will become more and more important to apply comparative evaluation tools in the full knowledge of their subtleties.

8. Conclusion

The $LCOE_{BEIS}$ metric is well established but lacks a clear theoretical justification. This paper provides one. It analyses and compares different cost of energy metrics by scrutinising their working principles and concludes that $LCOE_{BEIS}$ offers a useful metric, albeit with shortcomings and subtleties. While deterministic assessments of LCOE for CCGT power plants can be lower than those for offshore wind, when discount rates, inflation factors, and most critically, variability in feedstock prices are taken into account, the variability in LCOE for CCGT projects can complicate the picture. The authors urge the thoughtful use of this metric and the widespread adoption of Monte Carlo techniques in its calculation.

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Better estimates of LCOE from audited accounts: a new methodology with examples from United Kingdom offshore wind and CCGT.

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2019

Better estimates of LCOE from audited accounts – a new methodology with examples from United Kingdom offshore wind and CCGT

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Abstract

Around the world, government policies to support new renewable energy technologies rely on accurate estimates of Levelised Cost of Energy (LCOE). This paper reveals that such estimates are based on "public domain" data which may be unreliable. A new approach and methodology has been developed which uses United Kingdom (UK) "audited" data, published in company accounts that has been obtained from Companies House, to determine more accurate LCOE estimates. The methodology is applicable to projects configured within Special Purpose Vehicle (SPV) companies. The methodology is then applied to a number of UK offshore wind farms and one Combined Cycle Gas Turbine (CCGT) project, with cost data then compared to that presently in the public domain. The analysis reveals that recent offshore wind projects show a slightly declining LCOE and that public domain cost estimates are unreliable. But of most concern is that offshore wind farm costs are still much higher than those implied by recent bids for UK government financial support via Contracts for Difference (CfDs). The paper concludes by addressing further the question of how offshore wind projects can achieve the degree of LCOE reductions required by recent CfD bids.

1. Introduction

Offshore wind is expected to become an important component in the global future energy mix[1], including in the United Kingdom [2], Germany, Denmark, Japan, India and the United States of America[1,3]. The focus of this paper is on the United Kingdom (UK).

At present, offshore wind projects around the world are not directly cost-competitive with other forms of electricity generation [4]. In the UK, offshore wind projects are supported by government-mandated Contracts for Difference (CfDs). To secure financial support, developers are now bidding very aggressively, to the extent that the strike prices have fallen dramatically from around £150/MWh to £57.50/MWh between the first awards and the most recent auction rounds [5]. The capital and operating cost reductions implied by these bids are large, and are not supported by the overall trend of offshore wind farm costs for those projects already in operation.

Accurate evaluations of Levelised Cost of Energy (LCOE) are critical to policy choices and investment appraisal for offshore wind farms: the aim of this paper is to establish a new methodology to provide better information for policy and decision-making. This approach is based on calculating the LCOE applicable to energy projects undertaken through Special Purpose Vehicle companies (SPVs). The methodology is applied to a range of UK offshore wind farms in particular.

There is a considerable literature on costs and learning rates for offshore wind [4,6-14]. The literature on wind farm costs ranges from simple assessments of the comparative cost of electricity generation alternatives [4,6,7], through development of cost breakdown structures [8] and probabilistic assessments [9,10] to detailed evaluation of learning rates [11-13] and meta-analyses of learning rates [14].

The literature relies heavily on estimates of capital and operating costs from public domain sources. Ederer [15] has observed that cost data for offshore wind farms gathered from press reports or commercial databases can be unreliable, as “it is difficult to detect whether the figures were massaged”. In the case of online databases and reports from consulting companies, “where the original source is often not disclosed”…“it is not clear how the data were processed” [15]. In our own review of the literature we found that extant sources generally used for cost information are precisely those whose accuracy Ederer’s observations have thrown into doubt [15]. It is against this backdrop that this paper provides a new and robust approach to sourcing cost data which we believe should be more relevant, reliable and consistent than that currently in the public domain. It considers whether and why such data might be distorted, and compares data sourced using this approach to the publicly available data most commonly used in the literature.

The paper is divided into 8 sections. Section 1 introduces the paper. Section 2 reviews the relevant literature in the area of cost estimation with particular reference to offshore wind, and summarises the main sources of cost data and the uses to which it is put. Section 3 discusses the validity, robustness and potential for distortion of various data sources, while Section 4 sets out the new methodology used for gathering and working with audited data to provide the accurate capital and operating costs required to develop informed levelised cost of energy ("LCOE") calculations.

Section 5 comprises the main conclusions for UK offshore wind farms, although the method is equally applicable in other countries with significant offshore wind development (such as Germany and Denmark) and to other technologies (an example is provided for a Combined Cycle Gas Turbine - CCGT - power project). It includes sensitivity calculations on discount rate – a key factor in LCOE calculation. Section 6 compares the new results with data derived from other public domain sources commonly used by other researchers and shows that these public domain sources can be significantly different to cost data derived from accounts. Section 7 explores the implications for cost reduction targets for new wind projects in the context of recent CfD bids.

Section 8 discusses the new methodology and draws important conclusions.

2. Literature review

Cost comparisons of alternative electricity generation technologies are essential in informing policy choices. In a world transitioning from carbon-emitting thermal power generating technologies (such as gas and coal-fired power stations) to carbon-neutral and renewable choices (including offshore wind), a well-informed understanding of comparative costs must lie at the foundation of informed policy decisions.

The literature is rich with examples of cost comparisons and evaluation of cost trends in specific technologies. It is immediately obvious that where underlying cost data is of poor quality, any conclusions may be in doubt. This brief review considers some of this literature, setting out some of the uses to which cost data is put and examines the sources of cost data used in these examples.

2.1. Cost comparisons

The simplest application of cost data is to provide comparisons of the costs of energy alternatives. Such comparisons are widely used by Governments (e.g. the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) [6] and by commercial consultants such as Lazard, Ernst & Young and Arup [7,16,17].

BEIS expresses costs in terms of Levelised Cost of Energy (LCOE). LCOE is "the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWh" [6].

The formula for LCOE used by BEIS is set out in Equation 1:

$$LCOE = \frac{NPV_{Costs}}{NPE} = \sum_{t=1}^{n} \frac{C_t+O_t+V_t}{(1+d)^t} \bigg/ \sum_{t=1}^{n} \frac{E_t}{(1+d)^t} \qquad (1)$$

Where t is the period ranging from year 1 to year n, C_t the capital cost in period t (including decommissioning), O_t the fixed operating cost in period t, V_t the variable operating cost in period t (including fuel cost, and sometimes taxes, carbon costs etc), E_t the energy generated in period t, d, the discount rate, and n the final year of operation including decommissioning. A theoretical justification for LCOE was recently set out by Aldersey-Williams and Rubert [18].

BEIS calculates LCOE for renewable energy technologies (RETs) based on a report by Arup [17] which included updated "cost and technical assumptions for projects reaching FID (Final Investment Decision) between 2015 and 2030". Arup's report [17] outlines the data collection approach as involving a "broad mix of public, internal and stakeholder sources" and involving "manufacturers, projects developers and utility companies". However, it is clear that such data can be susceptible to manipulation by participants, who might be expected to be concerned to shape policymakers' opinions in favour of future projects.

Other commercial consultants, such as Lazard and Ernst & Young are even less specific about their data gathering approaches. Lazard's analysis of LCOE is based on "Lazard estimates" [7], while Ernst & Young state that they rely on "validated sources and use average input data". Ernst & Young add that their study is "based on publicly available information sources and average input data" [16]. Again, there is limited opportunity to confirm the validity of these data, which, if derived from public statements, may again be vulnerable to "massaging" or selective presentation by developers.

In recent literature, Partridge [4] compared thermal and renewable costs and emphasised the importance of reliable cost inputs, including capital and operating costs, and costs of finance, in building up the overall LCOE comparison. His focus was "to examine the issues that can confound generation cost calculations rather than to produce definitive cost estimates". In attempting to develop industry-wide LCOE calculations, he relied on public domain information and industry samples, rather than project specific and verifiable information and admitted that "even for "official" data, we should question the validity of cost estimates" [4].

2.2. Cost breakdown structures

Gonzalez-Rodriguez [8] sought to improve the quality of LCOE estimates by developing cost estimates for each significant cost area of offshore wind development. He obtained aggregated cost data from the 4C Offshore website [19] and component cost data from a range of technical, engineering and commercial sources, in order to develop expected costs for new offshore wind farm developments. In the light of Ederer's [15] and Partridge's [4] identification of the potential limitations of public databases, relying on the 4C Offshore dataset could leave Gonzalez-Rodriguez's analysis of past costs open to challenge, due to possible errors in this data and/or manipulation by developers' choices in data presentation. As will be shown in Section 6 – especially in the cases of the Dudgeon and West of Duddon Sands wind farms - the 4C Offshore data can be materially different to that from accounts data.

2.3. Probabilistic evaluation

Heck et al. [9] and Cartelle Barros et al. [10] both advocate probabilistic methods in LCOE estimation. These methods explicitly incorporate uncertainty in input data, and aim to provide insight into probable ranges of LCOE for different technologies, based on ranges of input data.

Cartelle Barros et al.'s data were "based on an extensive literature review of scientific articles, sector reports, real cases with published data and various interviews with an expert who has more than 40 years in the energy sector in the international arena" [10] while Heck et al. "carefully collected cost and operational data from a variety of sources" and compared their probabilistic results "with other LCOE studies" [9].

2.4. Learning rates

The learning rates achieved by onshore wind, and potentially to be expected by offshore wind, are of great interest to both developers and policymakers, as offshore wind is expected to be an important part of the decarbonised energy mix [2].

Evaluation of learning rates relies on high quality cost information and much work has been done in this area. Williams et al. [14] provides a meta-analysis of learning rates for wind power (including on- and offshore), drawn in large part from earlier work by Rubin et al. [20] and Lindman and Soderholm [21]. Unfortunately both of these earlier studies note that, as Lindman and Soderholm say "learning curve studies on offshore wind power are very few".

Other workers have undertaken more sophisticated work in relation to learning curves for wind: van der Zwaan et al. [11] took account of the variability of some of the exogenous variables (such as costs of steel and copper), which affect the cost trajectory. Their underlying data was drawn from 4C Offshore and other public domain sources.

MacGillivray et al. [13] assessed the learning rates required for marine renewables technologies (wave and tidal stream) to become competitive with "the benchmark technology" of offshore wind. Again, MacGillivray et al. employed offshore wind cost data from 4C Offshore [19].

2.5. Political and public argument

Not all observers of offshore wind costs are supportive – the Global Warming Policy Foundation's 2017 paper "Offshore Strike Prices" [5] analysed offshore wind costs to explore whether the anticipated cost reductions are supported by past cost trends. The Foundation expressed a concern that developers face little penalty if they fail to deliver the projects awarded CfDs, and this could lead to a shortfall in national power generation if these costs cannot in practice be achieved.

The Global Warming Policy Foundation used a number of data sources. It states that "the first is an EU-funded study by the FOWIND consortium (Facilitating Offshore Wind in India)" which covers various European sites. This report [3] recognises the difficulty of obtaining robust data, stating that "publically available information on the cost of offshore wind is challenging to obtain, with developers only ever quoting expected Capex figures (at financial close) in the public domain". Expected costs necessarily exclude cost overruns, which can add materially to project costs. The report also notes that there is no consistent basis on which figures are put into the public domain, with different sources including different aspects of wind farm costs (the example given is port upgrade costs to support wind farm activities).

The GWPF's other sources were "a set of UK-specific figures obtained by one of the present authors, Capell Aris, through careful gleaning of press stories and press releases" and the 4C Offshore database [5].

It is clear that publicly available cost data is widely relied upon as the foundation for a range of analyses. This paper focuses on a method for developing more reliable cost data than that currently in the public domain, allowing these analyses to be developed with better accuracy in future. It appears that existing public domain data is potentially inaccurate, inconsistent and possibly susceptible to "massaging" in support of a political or commercial agenda. These findings should be of significant concern to policy-makers and taxpayers.

3. Data sources – robustness and risks of distortion

This paper uses audited accounting data from wind farm SPV companies, which are considered to be a more reliable source of actual expenditure information than information put into the public domain by wind farm developers. This view is worthy of investigation.

3.1. Why might developers distort data?

Developers might wish to distort cost data available in the public domain for a number of reasons. These might include the desire to minimise tax, to present costs which would be considered acceptable to external commentators (to positively influence the wider debate on the acceptability and role of offshore wind), to influence policy (specifically in relation to policy support measures) or to mislead potential competitors in a competitive environment.

3.2. Public domain vs. audited accounts data

Public domain data, which is not subject to audit or investigation by the tax authorities, is clearly easier to distort than audited accounting information. In addition, third parties gathering and publishing cost information may have a particular agenda in relation to climate change (in either direction).

We believe that there are a number of factors which lead us to expect that cost data from audited accounts would less liable to distortion than other data.

3.2.1. Accounting standards and audit requirement

Accounting standards exist to help ensure that like for like comparisons are meaningful, and the accounts provide a “true and fair view” of the financial status of a business. While there is always scope for some flexibility within the standards, they do provide some boundaries.

Additionally, the requirement for audit confirms that the accounts for each SPV present a “true and fair view” and adhere to the accounting standards, providing some comfort that they should be substantially undistorted. It must be accepted that the audit process is not infallible.

3.2.2. Tax investigation

Another factor which is likely to encourage developers to keep their audited SPV accounts within reasonable bounds is the risk of a tax investigation. A public investigation of financial misreporting or distortion for reasons of tax optimisation would be likely to be both embarrassing and detrimental to future CfD applications.

3.2.3. Multi-ownership

SPVs are used to manage the risk of large and costly project developments, and frequently have multiple shareholders. This offers perhaps the best reason to consider SPV accounts as acceptably reliable - because the commercial interests and tolerance of the risk of making the distortion would have to align across all of the shareholders if the costs within the SPVs were to be distorted,.

An analysis of how different participants in London Array account for capital costs (shown in Figure 1) shows that while there are timing differences in recognition of capital spend between participants in the London Array project, the total spend is closely matched between participants. This close match provides some reassurance that the audited accounts for wind farm SPVs accurately reflect the actual underlying costs.

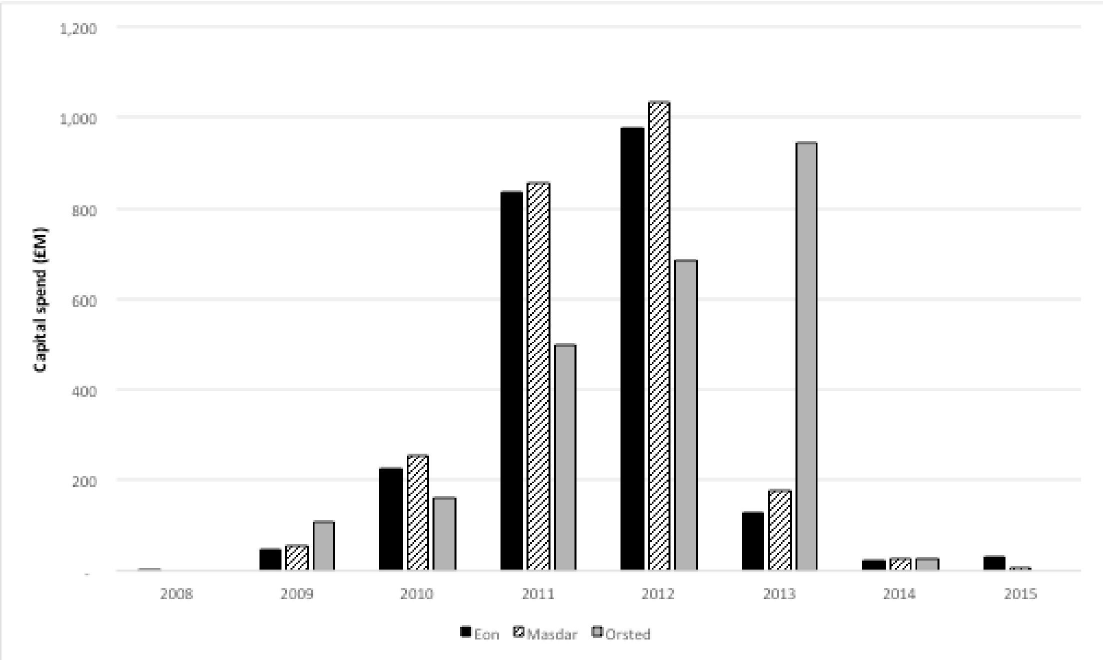

Figure 1 Timing differences in capital spend recognition - London Array (authors' analysis)

3.3. High or low?

The potential advantages to a developer of presenting the costs of offshore wind development as “higher than actual” or “lower than actual” are set out in Table 1.

Stakeholder	**Higher than actual**	**Lower than actual**
Tax position	Reduces local tax liability, shifts tax	Increases local tax liability, reduces tax

	liability to other (potentially lower rate) regime	liability in other (potentially higher rate) regime
Competitor impact	Distorts competitor perspective of cost base potentially encouraging competitor to accept higher costs	Distorts competitor perspective of cost base potentially driving competitor to attempt excessively low costs
Policy effect	Helps to make case for higher subsidy levels, but damages overall perception of technology viability	Helps make case to Government that technology is on viable trajectory but potentially impacts subsidy support
Public perception	Damages perception of technology as on viable trajectory	Enhances perception of technology as on viable trajectory

Table 1: Impacts of cost distortion (authors' analysis)

To summarise, it appears that there are various safeguards which suggest that while data in annual accounts may not subject from manipulation, it should nonetheless be more reliable than other data in the public domain.

4. Methodology

Ederer has pointed out that most offshore wind farm developments are undertaken through Special Purpose Vehicle (SPV) companies [15]. The use of SPVs allows parent company developers to insulate themselves from any liabilities potentially arising within the wind farm developments, and also makes asset sales easier, as shares in SPVs can easily be bought and sold as required.

However, a perhaps-unintended consequence of the commercial decision to isolate risks within SPVs is that detailed cost information is available in the public domain. As SPVs are legally constituted companies, they are required to submit audited accounts to the appropriate authorities. In the UK this is Companies House, which has recently made accounts for all UK companies publicly available at no cost. The methodology presented here exploits this data source to extract cost data from these published reports to build detailed assessments of actual LCOE.

This accounting information has some limitations: (1) accounting standards are not absolute, and offer some flexibility in presenting information; (2) accounts must be submitted within 9 months of the year end, so there can be a small time lag in data; (3) accounts may relate to a fractional interest in the underlying wind farm, and different participants may adopt different accounting treatments; (4) accounts contain very limited information on wind farm operational performance; and, (5) there are a number of stages of technical analysis which must be undertaken to extract the required information. These are detailed in Sections 4.8 and 4.9.

4.1. Source of Data

The operational offshore wind farms in the UK, and the related SPVs, are listed in Table 2. A database of the relevant SPV accounts has been compiled and analysed to extract cost information according to the methodology which follows.

In most cases, a single SPV accounts for all of the spend on a specific wind farm. In a limited number of cases, such as Gwynt y Mor and London Array, where multiple SPVs have interests in the underlying unincorporated joint venture, further analysis is required to identify total expenditures.

In Gwynt y Mor, where UK Green Investment GYM Participant Limited has held a constant 10% in the wind farm, it is a simple matter to gross up figures to provide total costs. At London Array, where ownership changes have complicated the picture, figures from Orsted Energy London Array Limited, Orsted Energy London Array II Limited, E.On Climate and Renewables UK London Array Limited and Masdar Energy (UK) Limited have been combined to allow compilation of an aggregated picture.

Some SPV names, and the interest they control in the underlying wind farm, have changed over time. Table 1 shows the current SPV names, and (where less than 100%) their current interest in the wind farm, as well as the dates for which accounts are available, and when the project transferred transmission assets to the Offshore Transmission Operator if applicable (see Sections 4.8 and 4.9).

Wind farm	**SPV Company(ies)** (Current names and current percentage interest)	**Accounts available**	**OFTO transfer date**
Barrow	Barrow Offshore Wind Limited	2001-2017	2011
Burbo Bank	Orsted Energy (Burbo) Limited	2002-2017	Not under

			OFTO
Burbo Extension	Burbo Extension Limited	2011-2017	2018
Dudgeon	Dudgeon Offshore Wind Limited	2003-2017	2018
Gunfleet Sands I	Gunfleet Sands Limited	2001-2017	2011
Greater Gabbard	Greater Gabbard Offshore Winds Limited	2004-2017	2014
Gunfleet Sands II	Gunfleet Sands II Limited	2007-2017	2011
Gwynt y Mor	UK Green Investment GYM Participant Limited (10%), Innogy GyM 2 Limited (10%), Innogy GyM 3 Limited (10%), Innogy GyM 4 Limited (30%), GyM Renewables One Limited (10%), GyM Offshore One Limited (15%), GyM Offshore Two Limited (10%), GyM Offshore Three Limited (5%)	2010-2017	2015
Humber Gateway	E.On Climate & Renewables UK Humber Wind Limited	2008-2017	2015
Inner Dowsing	Inner Dowsing Wind Farm Limited	2004-2017	Not under OFTO
Kentish Flats	Kentish Flats Limited	2001-2017	Not under OFTO
Kentish Flats Extension	Vattenfall Europe Windkraft GmbH (German company)	Not reviewed	Not reviewed
Lincs	Lincs Wind Farm Limited	2001-2017	2014
London Array	Orsted Energy London Array Limited (0%) (formerly CORE Energy Limited), Orsted Energy London Array II Limited (25%), E.On Climate and Renewables UK London Array Limited (30%), Masdar Energy UK Limited (20%), Boreas	2003-2017	2013

	(Investments) Limited (25%)		
Lynn	Lynn Wind Farm Limited	2001-2017	Not under OFTO
North Hoyle	NWP Offshore Limited	2002 -2017	Not under OFTO
Ormonde	Ormonde Energy Limited	2004-2017	2012
Race Bank	Race Bank Wind Farm Limited	2004-2017	2018
Rhyl Flats	Rhyl Flats Wind Farm Limited	2005-2017	Not under OFTO
Robin Rigg East	E.On Climate and Renewables UK Robin Rigg East Limited	2006-2017	2011
Robin Rigg West	E.On Climate and Renewables UK Robin Rigg East Limited	2002-2017	2011
Scroby Sands	E.On Climate and Renewables UK Offshore Wind Limited	2003-2017	Not under OFTO
Sheringham Shoal	Scira Offshore Energy Limited	2004-2017	2013
Teesside	Teesside Windfarm Limited	2009-2017	Not under OFTO
Thanet	Thanet Offshore Wind Limited	2004-2017	2014
Walney	Walney (UK) Offshore Windfarms Limited	2005-2017	2011/12
Walney Extension	Orsted Energy Walney Extension (UK) Limited	2011-2017	2016
West of Duddon	Orsted Energy West of Duddon Sands (UK) Limited	2008-2017	2015
Westermost Rough	Westermost Rough Limited	2007-2017	2016

Table 2: Wind farms and SPVs (authors' analysis)

4.2. Capital costs

Capital costs for each wind farm have been derived from the database for each year and for each wind farm. In order to identify capital costs, the additions to Fixed Assets have been extracted, and additions to Fixed Assets which do not represent cash expenditure (such as additions to the provision for decommissioning) are then removed. Capitalised interest, which is often treated as a fixed asset, is included in these costs, as it represents actual cash costs which are borne by the wind farm developer in completing the development.

For those wind farms which sold their transmission assets under the Offshore Transmission Operator Regulations (OFTO projects), the costs of these assets has been captured separately, to allow analysis of the OFTO impact on LCOE. This is discussed further in Section 4.9.

4.3. Operating costs

In order to evaluate LCOE, the cash operating costs are required. In accounting terms, both costs of sales and administrative expenses (which we define as total operating costs) are relevant costs in calculating the LCOE of the wind farm, so it is appropriate to derive the total operating costs by subtracting depreciation from the sum of costs of sales and administrative expenses.

For OFTO projects, these cash costs include OFTO charges from the date on which the OFTO transfer took place. This is discussed further in Section 4.9.

4.4. Grants

Some of the early projects were in receipt of capital grants. In some cases, grant receipts were shown as a credit to expenses (e.g. Burbo Bank, Kentish Flats, North Hoyle, Scroby Sands). Where this was the treatment, these amounts have been added back to yield accurate operating costs. In some other cases they were shown as interest income (e.g. Inner Dowsing, Lynn), or as other income (e.g. Barrow) and no correction is necessary. The corrections for grant income ensure that the operating cost figures used are accurate.

4.5. Inflation adjustment

The database comprises costs for each wind farm SPV for each year of development or operation. In order to compare each wind farm’s costs on a comparable basis, it is necessary to normalize for inflation effects. A general European inflation factor[1] has been applied to correct all figures to 2012 terms. 2012 has been chosen as it is the base year for strike prices under the UK Contracts for Difference arrangements, so it seems the most appropriate base year for this correction.

4.6. Energy production

Details of the month by month energy production from wind farms accredited under the Renewables Obligation (RO) is available from OFGEM's Renewables and CHP Register[22], albeit with a delay of around 4 months. This data has been downloaded and analysed. The ROC Register does not present project by project data before April 2006, and for the very limited number of offshore wind projects which were producing prior to this date, data has been extracted from the Renewable Energy Foundation website (which provides historic project by project ROC data before 2006) [23].

Wind farms operating under CfDs are not eligible for ROCs, but they are issued with Renewable Energy Guarantees of Origin (REGOs) which confirm the renewable origin of the electricity generated by these projects. OFGEM's Renewables and CHP Register [22] provides data on issued REGOs, allowing the same derivation of production performance as the ROC register.

For wind farms with limited production history data on the ROC or REGO registers, estimates of typical capacity factor can be derived from the performance of nearby offshore wind farms with longer production histories. If no nearby wind farms are available, typical average capacity factor can be used.

4.7. Projections

Offshore wind farms are typically expected to have an operating life of 20-25 years, and the earliest in this study began production only 15 years ago. It is therefore necessary to develop projections of costs and energy production over the full life of each project to establish a full life LCOE.

In this analysis, a base case has been defined, in which real operating costs and production are kept constant at the average level achieved by the wind farm since commissioning. In the case of OFTO projects, operating costs are projected from the average operating cost for years after the OFTO transfer to ensure inclusion of OFTO charges.

[1] The European index has been chosen as the single largest cost element, wind turbines, are generally produced in Denmark or Germany, making the European index appropriate.

Production projections have been based on average production levels from years of full production, defined as years in which production is greater than 60% of average production over the farm's productive life (to compensate for low production in the year of commissioning). For those wind farms which have only recently begun production, and there is only a very short production history, an average capacity factor of 48% based on BEIS assumptions [6] has been used. Of course, the performance of offshore wind farms can vary from year to year in response to the wind climate, but it is considered that using the average-to-date (where a meaningful time series is available) is a fair estimate over the full project life.

4.8. OFTO regime

Burges Salmon partner James Phillips, writing in Modern Power Systems, set out the basis for the Offshore Transmission regime and the principles of its operation [24].

He explained that under the "Third Package" of legislation on the liberalisation of energy markets, electricity generation and transmission assets were required to be "unbundled" – that is, not owned by the same entities. Accordingly, under powers in the Energy Act 2004, the Secretary of State implemented the Electricity (Competitive Tenders for Offshore Transmission Licences) Regulations 2009.

Under these regulations, wind farm operators which exported at 132 kV or more were required to sell their transmission assets to third parties (who were known as Offshore Transmission Network Owners, or OFTOs), who were empowered to earn a regulated return from these investments.

Accordingly, many of the offshore wind farms under development at that stage were required to dispose of their transmission assets. These wind farm developers/operators received a capital sum for the assets, and were then contractually bound to pay operating charges to the OFTOs for up to 20 years. This had the effect of converting capital and operating costs of building and operating these assets into purely operating costs [24].

A report by KPMG [25] suggested that OFTO investors were typically seeking and receiving returns of 200 basis points over LIBOR, or around 3%, on their investments. A review by the Competition and Markets Authority [26] suggested that costs of capital for utilities engaged in generation activities might be in the range from 8-10%. The OFTO regime therefore makes lower cost capital available for funding a significant part of the wind farm generation and transmission system, thereby reducing the costs of financing (and therefore the discount rate to be used in the LCOE calculation).

4.9. OFTO correction

Accounts for OFTO-governed projects typically include the build costs of the OFTO assets as additions to fixed assets (prior to their transfer to the OFTO operator) and the OFTO charges paid by the wind farm operator as part of the operating costs. If both of these costs are left in the LCOE calculation, the costs of the OFTO are effectively counted twice.

The capital costs of the OFTO assets are deducted from the wind farm total build costs, while the OFTO charges are left included within operating costs. This approach describes the economic situation for wind farm operators as it prevails under the OFTO regime.

Wind farm accounts generally show a reduction in fixed assets when the OFTO assets are transferred to the OFTO operator. The Fixed Assets note to the accounts generally shows the cost of the OFTO asset which had been borne by the wind farm up to that point, and this sum can be subtracted from the total capital costs derived from Fixed Asset additions. Care is taken to ensure that the undepreciated cost is subtracted from the total fixed asset additions, to ensure that the full cost is removed from the capital costs in the LCOE calculation.

Where there is a gain or loss on sale, this is included within the operating costs for that year, so the analysis correctly shows the cash effects for the developer (although it is not included in the average calculation of operating costs, to ensure that these reflect true costs of operation).

4.10. Discount rate

The discount used in the LCOE calculation has a significant effect on the outcome. Discount rates used by investors should reflect the risk implicit in the project, and it would be reasonable to expect the discount rate applying to CfD projects, on which the revenue risk is much lower than for ROC projects, to be lower. Aldersey-Williams and Rubert [18] found that reducing the discount rate from the 8.9% currently applied by BEIS for offshore wind projects to the 7.8% it uses for CCGT projects resulted in a reduction in LCOE of 6%. Section 5.5 evaluates the impact of using a lower discount rate in the CfD projects.

4.11. LCOE calculation

These actual and projected figures are combined into the LCOE calculation, as defined by BEIS and shown in equation 1. A discount rate of 8.9% (in line with BEIS's discount rate choice [6]) has been applied, and some sensitivities undertaken (see Section 5.5).

The LCOE in these calculations includes the costs of the wind farm including its connection to the National Grid (either as a direct cost for non-OFTO projects or through OFTO fees for OFTO projects). The next section sets out the results of calculating LCOE for the UK's operational wind farms using this approach.

5. Results

5.1. Overview of results

The LCOE has been calculated for all UK projects which had reported production before the end of 2017, set out in order of commissioning year, as shown in Table 2. In addition, the real capital cost per MW installed is evaluated, as this is a basis on which these data may be compared with public domain sources.

5.1.1. LCOE results – all projects

The summary results for all projects are shown in Table 2 and the overall trend of costs in Figure 2, which shows the LCOE for projects arranged in chronological order of commissioning.

Wind farm	**OFTO status**	**First production**	**LCOE (£/MWh)**
North Hoyle	Non OFTO	2003	77.35

Kentish Flats	Non OFTO	2006	66.43
Scroby Sands	Non OFTO	2006	104.83
Barrow	OFTO	2006	87.15
Burbo Bank	Non OFTO	2007	86.89
Inner Dowsing	Non OFTO	2008	96.59
Lynn	Non OFTO	2008	101.54
Rhyl Flats	Non OFTO	2009	125.62
Gunfleet Sands I and II	OFTO	2009	121.67
Robin Rigg	OFTO	2010	135.49
Thanet	OFTO	2010	158.69
Greater Gabbard	OFTO	2011	136.62
Ormonde	OFTO	2011	149.08
Walney	OFTO	2011	120.37
London Array	OFTO	2012	139.89
Sheringham Shoal	OFTO	2012	150.34
Teesside	Non OFTO	2013	235.96
Lincs	OFTO	2013	166.053
Gwynt y Mor	OFTO	2014	179.18
Westermost Rough	OFTO	2014	120.82
West of Duddon	OFTO	2014	72.11
Humber Gateway	OFTO	2015	147.13
Burbo Bank Extension[1]	OFTO	2016	146.95
Dudgeon[1]	OFTO	2017	104.07
Galloper[1]	OFTO	2017	133.89
Race Bank[1]	OFTO	2017	118.09
Walney Extension[1]	OFTO	2017	100.24

Table 3: LCOE (all projects, authors' analysis)

[1] due to short production histories for these wind farms, some assumptions are required. A typical modern offshore wind farm capacity factor of 48% has been applied in line with BEIS assumptions[6];

an average operating cost of 37/MWh has been applied based on the average post-OFTO operating costs found in this analysis and OFTO capital costs have been taken from the most recent accounts. These figures should be treated with some caution.

The same data is presented graphically in Figure 2.

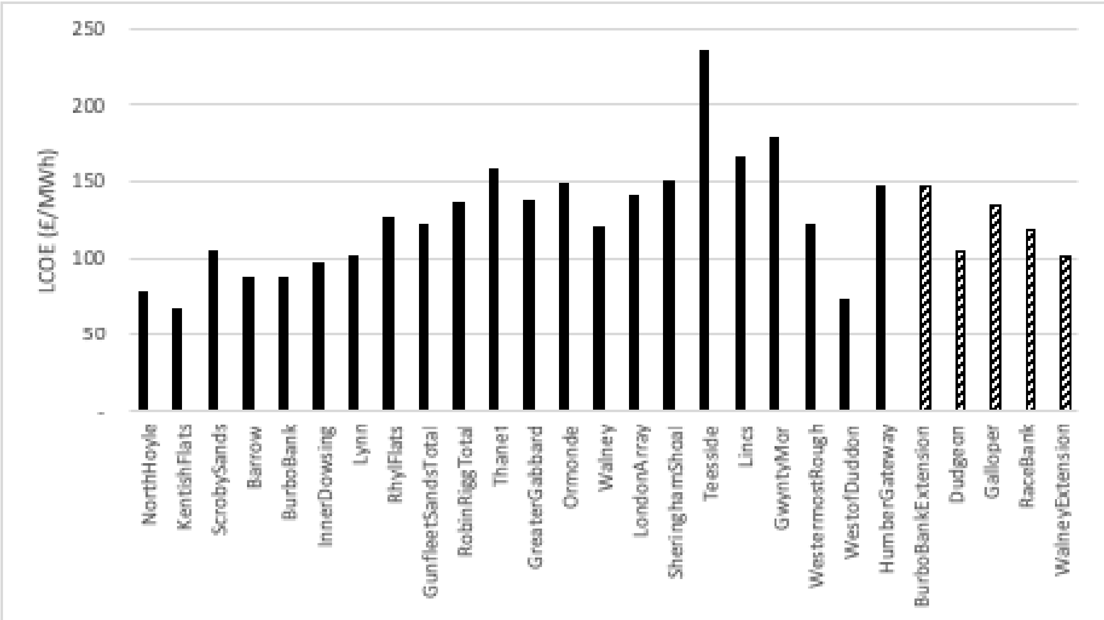

Figure 2: LCOE for all projects, chronological order by commissioning (authors' analysis). (NB solid bars show data for wind farms with full accounts-based and historic production data, striped where assumptions are used on capacity factor, OFTO transfer and operating costs)

5.2. LCOE Outliers

The Teesside project immediately stands out as having an anomalously high LCOE, while West of Duddon Sands appears low.

5.2.1. Teesside

The Teesside project employed 2.3MW turbines. These were outdated by its commissioning date of 2012, as the typical turbine size by this date was 3.6MW or larger.

This turbine choice, which obviously necessitated more foundations and installation work than a larger turbine size, along with significant delays in its consenting and development process, combined to push up the LCOE. Analysis of ROC data from the ROC Register [22] shows that Teesside also had a low capacity factor of 15-25% over its first years of operation, further increasing the LCOE. A sensitivity analysis in which it is assumed that the project can achieve a more realistic capacity factor of 35% for future years shows the LCOE reducing to £221.81/MWh. While this is slightly closer to the typical LCOE at that time, it suggests that the majority of the excess LCOE is due to capital cost and schedule overruns.

5.2.2. West of Duddon Sands

The LCOE for the West of Duddon Sands project appears to be exceptionally low. This project had a development timescale comparable to its neighbour at Walney and achieved a similar ramp up in production. The key differentiator was the low cost per MW installed relative to Walney. This is inferred to be due to improvements in installation process and costs, as both projects deployed Siemens 3.6MW turbines (although Walney used both 107m and 120m diameter variants).

5.3. LCOE trends

Figure 2 shows an upward trend in LCOE for offshore wind for projects developed up to and including Thanet, from less than £100/MWh to more than £150/MWh (excluding the Teesside project).

Many commentators, such as Greenacre et al., Heptonstall et al., Ioannou et al. and Voormolen et al. [2, 27-29] have linked the original increasing cost trajectory to the trend towards situating wind farms in deeper water, further from shore.

After excluding the apparent outlier of Teesside, it appears that LCOE increased gradually to a maximum of around £150/MWh in Thanet, after which it began a gradual decline, although project LCOEs vary widely.

A review of the trends would suggest that new wind farms are now achieving LCOE of around £100/MWh, which is still considerably above the level implied by the most recent CfD bids of £57.50/MWh.

5.4. LCOE sensitivities

The LCOE metric is sensitive to capital cost, production forecasting and discount rate. The methodology adopted in this paper addresses uncertainty in capital cost by using data from accounts, but the effect of uncertainty in production and choice of discount rate requires analysis.

5.4.1. Production forecasting

A recent study by Staffel and Green [30] used ROC data to evaluate trends in onshore wind farm performance with the “age” of turbines. They found that wind farm performance declined by 1.6%+/-0.2% per annum as turbines aged. Their dataset was limited to onshore wind farms, as they recognised that there was insufficient depth in the offshore fleet to provide a meaningful basis for analysis. This remains the case. However, it is recognised that the same factors which lead to performance degradation onshore are likely to be equally valid offshore. Accordingly, a sensitivity analysis has been undertaken to assess the impact on LCOE of an annual performance degradation of 1.6% in output.

The impact on LCOE for the offshore wind farms evaluated here is an increase of between 1% and 8%, depending on the date of commissioning date of the wind farm. The LCOE impact is greater for the most recently commissioned wind farms, as the older wind farms’ LCOE is more heavily based on actual performance.

5.5. Sensitivity to discount rate

As discussed in section 4.10, the discount rate used in the LCOE calculation has a significant effect on the outcome. The introduction of Contracts for Difference has significantly changed the risk profile of offshore wind investment and it can be argued that the discount rate for CfD projects relative to ROC projects should be significantly lower. Aldersey-Williams and Rubert[18] found that current UK offshore wind projects were being financed with 75% debt/25% equity, with the debt secured at rates of 3.5%-4%. If an equity return of 15% is assumed, the resulting WACC is less than 7%. In this sensitivity, a discount rate of 7% has therefore been applied to the CfD-supported projects. Table 4 shows that this lower discount rate reduces the LCOE by around 10% for these projects.

	LCOE (£/MWh)	**LCOE (£/MWh)**

	Discount rate at 8.9%	Discount rate at 7%
Burbo Bank Extension	146.95	130.02
Dudgeon	104.07	92.71
Galloper	133.89	119.18
Race Bank	118.09	105.46
Walney Extension	100.24	90.74

Table 3: Impact of reduced discount rate for CfD wind farms LCOE (authors' analysis)

5.6. Capital cost per MW installed

The capital cost per MW installed is another widely used comparative metric. It is shown, in 2012 real terms, for each project in Figure 3. This shows a clear increase from £1.5-2 million/MW for the early projects, to £2-4 million/MW for more recent projects.

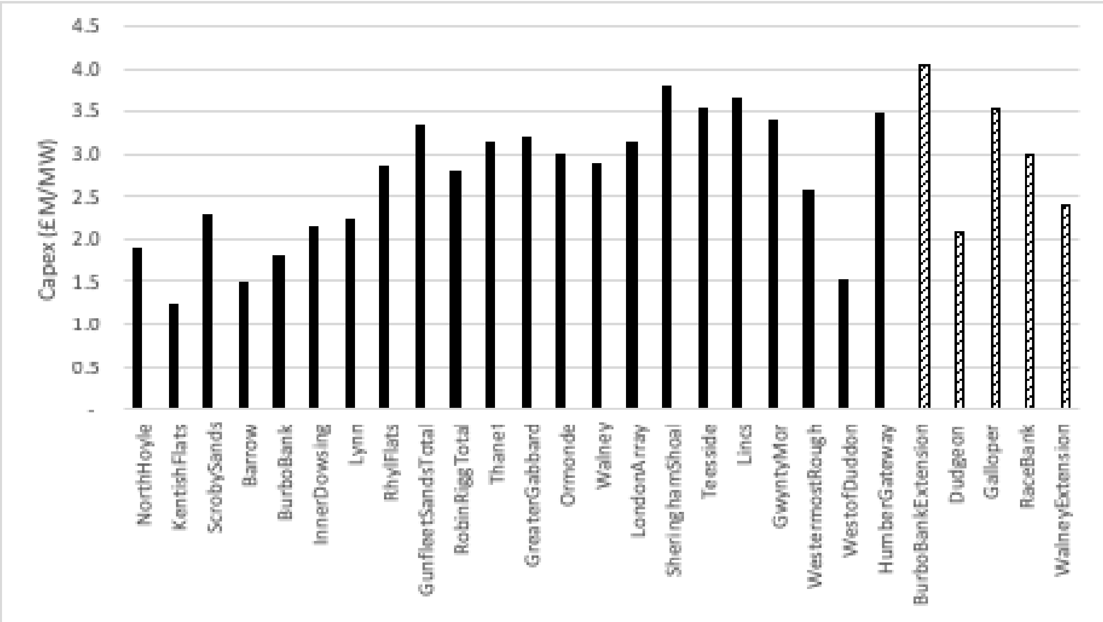

Figure 3: Capital cost per MW installed (2012 real terms), authors' analysis (NB solid bars show data for wind farms with full accounts-based and historic production data, striped where assumptions are used on capacity factor, OFTO transfer and operating costs)

The increase in LCOE in more recent projects is proportionately less than the increase in cost per MW, suggesting that production performance has increased, development timescales have been compressed or operating costs have been reduced, or a combination of these factors, over successive generations of wind farm development.

This analysis is consistent with Ernst and Young's 2009 report [31], which noted that "average capital costs have doubled over the last five year to c. £3.2million/MW; the cost increase appears largely driven by supply chain constraints for components (e.g. wind turbine generators) and services (e.g. installation)". It is also consistent with anecdotal evidence from informal discussions with developers, who often claim that turbine prices increased after the introduction of ROC banding (and therefore the higher revenue expectations among developers). Rhyl Flats was among the first offshore wind farms to be built in the foreknowledge of higher support under the RO, and shows a cost per MW installed significantly higher than earlier projects.

5.7. International comparisons

International data [32] suggest that the overall cost trend of UK offshore wind is broadly in line with international cost trends in wind turbine costs. Figure 4 shows wind turbine prices in the US and globally [32] and shows a peak in around 2008 – when the Thanet project was procuring its turbines [19]. The data in Figure 4 comes from a range of sources, including "financial and regulatory filings, as well as press releases and news reports" [32] and is therefore considered to be meaningful. A better comparison would require accounts-based LCOE estimates for international projects, which lie beyond the scope of this paper, but would be an interesting direction for future research.

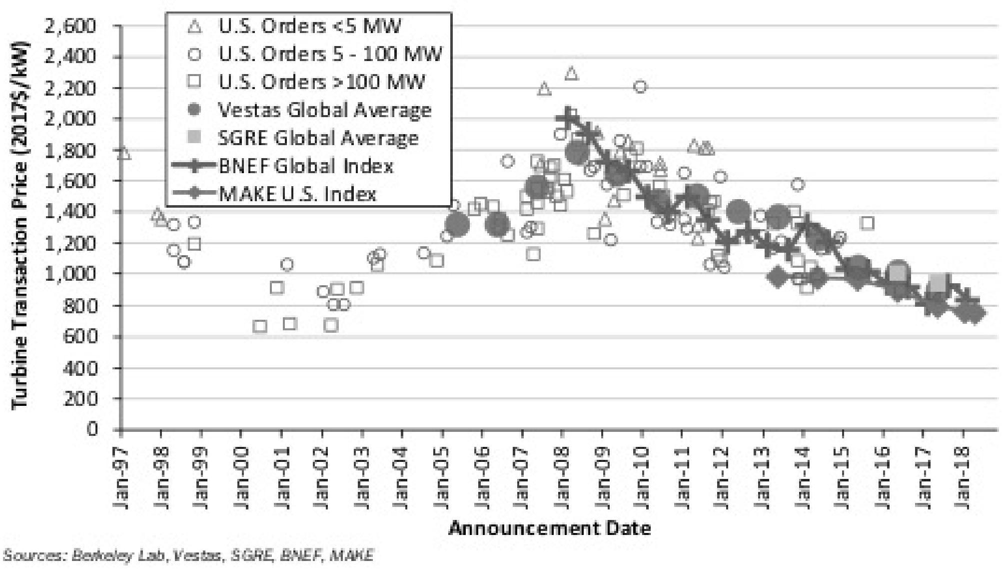

Figure 4: International turbine price trends (from [32])

While the overall cost trend in UK offshore wind is now downward, the degree of reduction is less than for turbine prices as noted in the US Department of Energy's report. This is inferred to reflect the siting of UK wind farms in more distant offshore locations and deeper water, driving up installation and foundation costs.

5.8. CCGT example

The same methodology has been applied to the Coryton CCGT power station, which was built between 1999 and 2001 and began commercial operation in 2002. Coryton CCGT is operated through a SPV called Coryton Energy Company Limited which files accounts at Companies House. Analysis of the accounts shows a total real (2012) capital spend of £71 million, and annual operating costs varying between £75 million and £330 million with the variation driven very largely by fuel prices. An average of £110 million, based on the average real operating cost over the project's operating life to date has been applied for forecasting future opex.

Production data is not available for the full operating life of the project. Data is available for the period 2010-2014 (2015 forecast) [33] and this has been applied in the model. Where production data is not available, an average load factor of 34% has been used. This is the average load factor for CCGT for 2012-2016 reported in Digest of UK Energy Statistics, Table 5.1 [34] and is comparable to the average load factor of 32% for the period for which project data is available. A discount rate of 7.5% as applied by BEIS for this technology [6] has been used. The resulting LCOE (2012 real terms) is £62.63/MWh.

The methodology is demonstrated to be applicable to any project organized in a SPV where meaningful production data can be found.

6. Comparison with other work

As previously noted, researchers, analysts and other professional commentators on offshore wind costs have generally used data compiled from public domain sources [4, 6-14]. In general, their cost databases are not published, making comparison of costs developed from the approach detailed here with publicly gleaned information difficult. However, two full data sources are available for comparison.

The datasets are the 4C Offshore website [19], which we believe sets out nominal (money of the day) costs, and the Global Warming Policy Foundation's report [5] which makes corrections for inflation and reports in 2012 terms. Neither of these datasets evaluates LCOE but both allow for evaluation of the capital cost per installed MW.

These data are set out in Table 5 for the wind farms capable of analysis using the accounts-based method set out here.

Name	**This analysis (£ million**	**4C Offshore (£**	**GWPF (£ million**

	/MW)	million /MW)	/MW)
Barrow	1.49	1.37	1.53
Burbo Bank Extension	4.05	3.15	NA
Burbo Bank	1.79	1.53	1.10
Dudgeon	2.09	3.73	3.44
Greater Gabbard	3.21	3.28	2.98
Gwynt y Mor	3.41	3.33	3.33
Humber Gateway	3.48	3.36	3.23
Inner Dowsing	2.15	1.54	1.63
Kentish Flats	1.22	1.17	1.57
Lincs	3.66	3.70	3.63
London Array	3.13	3.23	2.80
Lynn	2.22	1.54	1.63
North Hoyle	1.88	1.35	1.63
Ormonde	3.00	2.98	3.68
Rhyl Flats	2.84	2.11	2.31
Robin Rigg	2.79	2.19	2.36
Scroby Sands	2.30	1.28	1.50
Sheringham Shoal	3.78	3.42	3.47
Teesside	3.53	3.22	3.16
Thanet	3.14	3.00	3.11
Walney	2.89	3.43	3.39
West of Duddon Sands	1.50	3.22	3.11
Westermost Rough	2.58	2.95	3.38

Table 5*: Capital cost per MW; authors' analysis,* [5,19].

It is clear that these estimates vary widely, with the main drivers of cost per MW being turbine costs, distance from shore, foundation type and installation strategy [35].

Figure 5 shows the percentage difference between the figure for capital cost per MW from the analysis of accounts undertaken here and two relatively complete public sources - 4C Offshore [19] and the Global Warming Policy Foundation [5]. The close parallels between the 4C and GWPF data can be explained as the GWPF data is gathered, at least in part from 4C Offshore.

In many cases, the public domain cost figures are c. 20% lower than the capital costs from accounting data, although there are cases where the public domain data significantly higher, notably Burbo Bank, Kentish Flats, Ormonde, Walney, West of Duddon Sands and Westermost Rough.

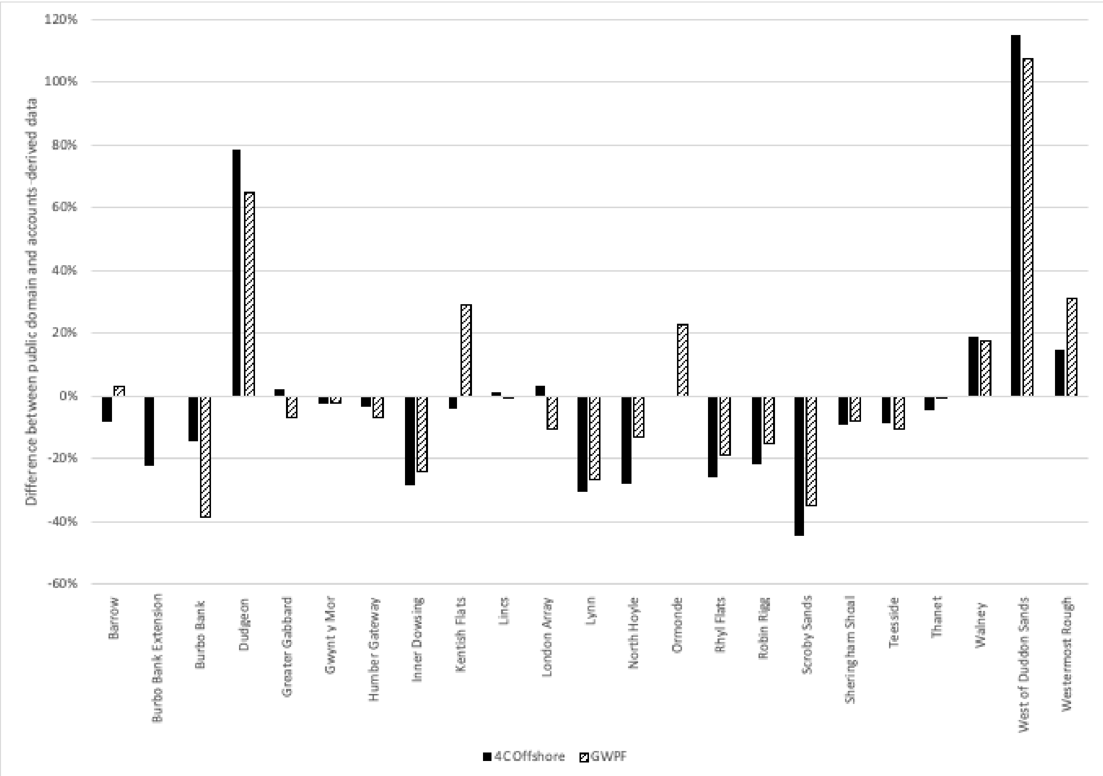

Figure 5: Percentage difference between public data and this analysis; authors' analysis and [5, 19].

As capital cost/MW is the most important factor in assessing the LCOE for offshore wind projects (as operating costs only typically contribute around a quarter of the LCOE, while Capex contributes the majority [6]), these discrepancies will have a significant effect on estimates of LCOE in the existing literature. These discrepancies further demonstrate that public domain data is not wholly to be relied on.

7. Required cost trends

This analysis has shown that there may be a gradual downward trend in LCOE for UK offshore wind farms since about 2010. It is interesting to consider the LCOE which offshore wind must achieve in order to offer commercial returns at the prices at which recent CfDs have been awarded.

The most recent CfDs were awarded at a price (in 2012 terms) of £57.50/MWh, while the analysis here shows that modern wind farms typically have a LCOE of c. £100/MWh. Although as Aldersey-Williams and Rubert make clear [18] the LCOE and strike price are only the same in a zero-inflation world, it is nonetheless clear that very significant reductions are required to wind farm costs to offer economic projects in the context of current strike prices.

One key area in which LCOE can be reduced is by reducing the discount rate used for the calculation. The discount rate reflects the investment risk in the project, and the introduction of CfDs significantly reduces the revenue risk for the developers. As noted in Sections 4.10 and 5.5, lower discount rates, reflecting the lower risk of CfDs, help to reduce wind farm LCOE.

8. Discussion and conclusion

This paper has presented a new methodology for determining LCOE in cases where reliable audited data is available. It is observed that much of the existing literature examining costs and trends in offshore wind is potentially compromised by inaccuracy, inconsistency or selective presentation by developers.

Application of this new methodology suggests that the LCOE for new wind farms is still significantly higher than the level of recent CfD strike price bids. There are some encouraging signs, however, as the recent West of Duddon Sands project has a LCOE of less than £100/MWh.

It is clear that continuing LCOE reduction will require continuing technological evolution, as well as more efficient operating practices and lower discount rates to reflect the reduced revenue risk under CfDs. Technological improvements are likely to be dominated by the continuing trend to increasing turbine capacity. This is exemplified by GE’s recent announcement of a 12MW turbine [36]. Larger turbines allow more installed capacity per foundation, and therefore offer economies of scale in manufacture and installation. Fewer turbines also offer economies of scale in operational costs, as the costs of maintaining a turbine are largely determined by access costs, rather than by each turbine's rated capacity. Larger wind farms also make alternative operational strategies viable, as demonstrated by the emergence of Service Operations Vessels [37] - vessels based at sea within the wind farm, offering 24/7 service and higher reliability and production.

The LCOE result is also determined by the discount rate used, just as the economic returns of the wind farm are driven by its capital structure. The introduction of CfDs reduces the revenue risk for developers relative to wind farm projects supported under the RO. It is reported that this reduced risk can allow the use of a higher proportion of debt than RO projects [38, 39], thereby justifying the use of a lower discount rate and reducing the LCOE.

This paper has found that much of the analysis of offshore wind costs, and the trends they show, is based on public domain data which are shown to be inconsistent with cost data taken from audited accounts, which are considered to be more reliable. Significant discrepancies in capital cost per MW have been found, with public domain data found to be both higher and lower than data from accounts. As a result, policy choices based on these data may be flawed with important effects on the future energy mix.

More widely, the methodology is seen to be equally valid for any power project configured as a Special Purpose Vehicle and where production data is available or can be reasonably estimated.

In conclusion this paper has presented and applied a new methodology for developing LCOE data and applied it to a number of offshore wind farms and to one CCGT project. The new methodology, explained here in detail for the first time, offers a robust route to evaluation of key data and trends in power generation costs, to inform better policy choices, around the world.

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Analysis of United Kingdom offshore wind farm performance using public data: improving the evidence base for policymaking.

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