Life cycle assessment of the Seagen marine current turbine

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The manuscript was received on 30 August 2007 and was accepted after revision for publication on 13 December 2007.

DOI: 10.1243/14750902JEME94

Abstract: The world's first commercial-scale grid-connected tidal current energy installation will feature the Seagen marine current turbine developed by Marine Current Turbines Ltd. With potential for the manufacture of significant numbers of such devices there is a need to assess their environmental impact and, in particular, their life cycle energy and carbon dioxide (CO_2) performance. This paper presents an analysis of the life cycle energy use and CO_2 emissions associated with the first generation of Seagen turbines. The detailed assessment covers the embodied energy and CO_2 in the materials and manufacturing of components, device installation, and operation along with those for decommissioning. With relatively conservative assumptions, and despite the early stage of development, the study shows that at 214 kJ/kWh and 15 g CO_2/kWh, the respective energy and carbon intensities are comparable with large wind turbines and very low relative to the 400 to 1000 g CO_2/kWh typical of fossil-fuelled generation. The energy payback period is approximately 14 months and the CO_2 payback is around 8 months. The embodied energy and carbon show limited sensitivity to assumptions with environmental performance remains excellent even under the most adverse scenarios considered. Materials use is identified as the primary contributors to embodied energy and carbon with shipping also significant. Improvements in the environmental impact of the Seagen can be achieved primarily by increased structural efficiency and the use of alternative installation methods to increase recovery of steel at decommissioning.

Keywords: life cycle analysis, marine currents, tidal energy, tidal stream

1 INTRODUCTION

Concerns over climate change are driving attempts to create a low carbon economy. Renewable energy is expected to play a key role in this, and the Government of the United Kingdom (UK) have implemented the Renewables Obligation, which requires electricity generators to supply 10 per cent of electricity from renewable sources by 2010, with an aspiration of 20 per cent by 2020 (targets in Scotland are more significant). The UK's marine energy resources are believed to have the potential to supply 15–20 per cent of electricity demand [**1**]. A key component of the marine resource is tidal energy and, while there has been much discussion of barrages in the Severn and Mersey, it has not been commercially exploited. However, an alternative method for extracting energy from tidal currents is approaching commercial reality.

Tidal stream technology is one of the most recent forms of renewable energy to be developed. The advantages offered by tidal stream technology include [**2–3**]: no pollution and negligible environmental impact, entirely predictable energy delivery as currents are driven by gravity rather than weather, areas of potential development are generally underutilized, and the energy intensity is higher than other renewables. The power that can be drawn from tidal currents is highly sensitive to the velocity of currents and output will vary depending on the location of the turbine. The basic requirements for cost-effective tidal stream power generation are typically a mean spring peak velocity exceeding 2.25–2.5 m/s in a 30–40 m depth of water. Various sites around the UK

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such as the Pentland Firth (northern Scotland) and Alderney Race (Channel Islands) have been identified with the potential to supply energy on the multi-gigawatt scale [**4**].

One of the devices designed to harness this resource has been developed by Bristol-based Marine Current Turbines Ltd (MCT). Their Seagen turbine has twin underwater rotors deployed on a steel monopile. It will shortly be deployed at Strangford Narrows at the entrance to Strangford Lough in Northern Ireland and will be the first full-scale commercial prototype tidal turbine. Success for the project could lead to development of a programme of tidal current farms involving manufacture of a large number of Seagen devices. As such, it is important that the environmental impact of the Seagen is evaluated and one of the key aspects is its life cycle energy and carbon dioxide (CO_2) performance.

The only existing life cycle studies of marine energy converters have been first-order estimates of wave energy device carbon and energy intensity based on the mass of structural steel. Banerjee *et al.* [**5**] estimate the carbon intensity of the Pelamis wave device to be just under 40 g CO_2/kWh while the Carbon Trust [**1**] suggest that an unnamed wave device has a carbon intensity of 25–50 g CO_2/kWh and carbon payback in the region of 14 to 21 months.

The current paper sets out a detailed life cycle analysis of the Seagen tidal current turbine, which is believed to be the first analysis published for this technology. It evaluates the energy consumption and CO_2 production involved in each stage of its life cycle from 'cradle to grave' and compares these with other electricity generating sources. These figures allow derivation of the energy and the CO_2 payback times.

The paper is set out as follows. Section 2 briefly introduces the concept of life cycle analysis, outlines the features of the Seagen turbine and sets out the scope of the study. Section 3 provides a detailed breakdown of the assessment while section 4 presents the embodied energy and CO_2 for the device and sets the findings in context. Conclusions are provided in section 5.

2 LIFE CYCLE ASSESSMENT OF A TIDAL STREAM TURBINE

2.1 Life cycle assessment

Life cycle assessment (LCA), also known as a cradle to grave analysis, is an assessment of all the environmental impacts of a product, process or service within its complete life cycle. LCA has its roots in the 1960s when concern over rapid depletion of fossil fuels led to an approach that allowed understanding of the impacts of energy consumption [**6**]. LCA can identify energy and materials use and waste released to the environment, as well as evaluation and implementation of opportunities for improvements. LCA studies should comply with the international standard ISO 14040, which specifies the general framework, principles, and requirements for conducting and reporting such assessments [**7**]. LCAs have been applied to a range of electricity generating technologies including nuclear [**8**], fossil-fuelled plant [**9**], and renewables such as wind [**10–14**].

LCAs can be used as a product or process design improvement tool, helping designers and engineers to identify the environmental factors attributed to specific materials or life cycle stages, and ultimately allowing sound and informed decisions and improvements to be made. The LCA will also be of interest to potential investors, energy and government authorities who may consider the environmental implications of the product before investing or commissioning such a project.

LCA addresses only the environmental issues that are specified in the goal and scope and is therefore not a complete assessment of all environmental issues of the system under study. Limitations include the system boundary not encompassing all possible processes, inputs, or outputs; the non-availability of inventory data leading to assumptions and/or omissions; and inadequate quality of inventory data leading to error [**7**].

The life cycle of the Seagen marine current turbine consists of a series of stages, as illustrated in Fig. 1. Materials and manufacturing includes the entire method of manufacturing the turbines components, from raw material extraction and processing through to further component treatment. Transportation and installation includes energy consumption and emissions from the transportation of components to the assembly site and then on to the installation site. It also includes all materials and processes used during the installation procedure. Operations and maintenance (O&M) includes energy and emissions related to any process or materials used during operation and maintenance throughout the turbines lifetime. Transportation to the installation site, repairs, and replacement materials are included. Decommissioning and disposal includes transportation to and from the site at the end of the life cycle,

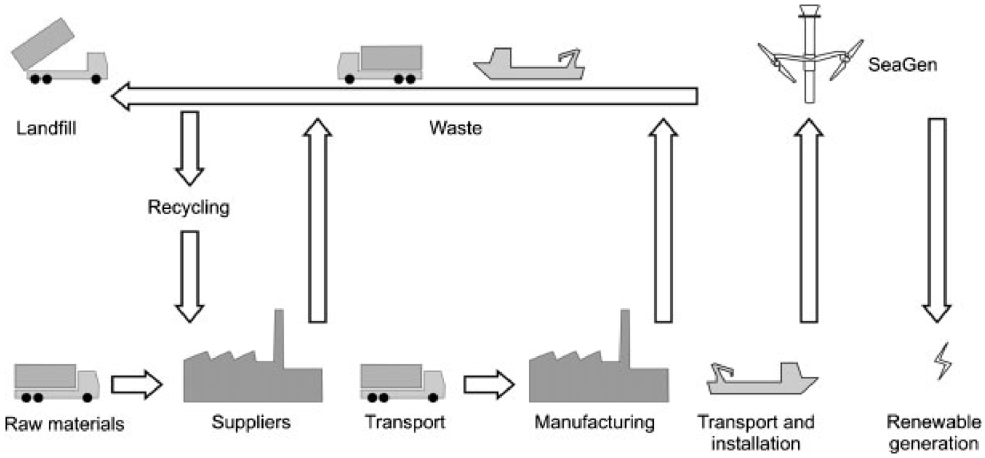

Fig. 1 Seagen life cycle stages, after references [**10**] and [**11**]

energy, and emissions related to the dismantling process as well as the effect of recycling or disposal of materials.

2.2 The Seagen marine current turbine

MCT was set up to pioneer the technical and commercial development of tidal stream turbines and has developed a novel method of extracting power from marine currents [**15**]. The 300 kW prototype, SeaFlow, installed in the Bristol Channel in May 2003, resembles a wind turbine as it is has an axial flow turbine mounted on a tubular steel tower. The 1.2 MW production version, Seagen, extends the concept with twin 16 m diameter axial flow rotors mounted on a crossbeam either side of the steel tower. Lift legs run either side of the tower providing the capability to lift the crossbeam and rotors above the surface for maintenance. The platform and pod sit on top of the tower. An illustration of the Seagen turbine is shown in Fig. 2.

The Seagen is in the process of being installed at Strangford Narrows at the entrance to Strangford Lough in Northern Ireland and extensive environmental assessments and monitoring have been carried out [**16**]. The characteristics and features of this development are assumed in this assessment. Harmonic analysis carried out at the site provided distributions of tidal current flow velocities which, when combined with the Seagen power curve (both Fig. 3), allowed prediction of the annual energy output. The potential annual energy production from the turbine is estimated at 5038 MWh. However, adjustments for predicted maintenance periods reduce this to 4736 MWh/year (assuming 94 per cent availability); this assessment assumes the lower production level. Table 1 gives a summary of the technical specifications.

2.3 Scope of assessment

The assessment analyses all incoming and outgoing materials and required processes throughout the 20-year life cycle of the Seagen marine current turbine, including foundations and grid connection. The

Fig. 2 Artist's impression of the Seagen marine current turbine

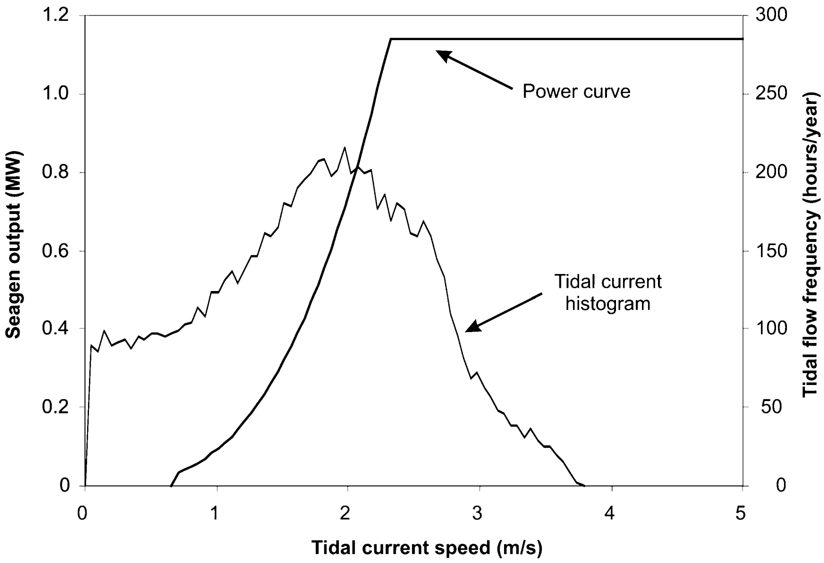

Fig. 3 Tidal current histogram for Strangford Narrows and Seagen power curve

system boundary indicates what is, and what is not, included in the analysis. This study achieves a 'cradle to grave' boundary by considering all energy input and carbon emissions from the extraction of the raw materials used in manufacture from their natural state to the complete disposal of the machine at its end-of-life (Fig. 1). Physically, the system boundary ends at the end of the sub-sea cable with all parts of the onshore electricity network outside the scope of this study.

In line with comparable assessments for other generating technologies, the energy and emissions associated with the manufacture of capital plant and machinery used during the Seagen life cycle have been excluded but the much more significant operational impacts (e.g. electricity and fuel consumption) are included. Energy and emissions associated with capital plant (e.g. machinery) has been restricted to operation (e.g. fuel/electricity consumption) and excludes any emissions owing to their manufacture. In line with Department for Environment and Rural Affairs (DEFRA) guidelines [**17**], it is assumed that electricity consumed throughout the life cycle comes from the UK grid and has an average CO_2 intensity of 0.43 kg CO_2/kWh.

Table 1 Technical specifications of Seagen Marine Current Turbine

Parameter	Value
Rated power	1.2 MW
Capacity factor	48%
Rotor diameter	16 m
Design life	20 years
Reliability	> 90%
Overall efficiency	89%
Design rotor power coefficient	0.45
Cut-in speed	0.7 m/s
Rated speed	2.25 m/s

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 Procedure

The collection of inventory data relating to the components and life cycle stages of the Seagen turbine was based on many sources of information supplied by MCT including a bill of materials, mass breakdown of main components, component drawings, the Seagen environmental statement [**16**], and data gathered from meetings with MCT staff.

The bill of materials listed over 600 components used in the turbine, the supplier, and cost. Assessing every component was infeasible within the available timescale so the priority was to establish the components with significant embodied energy and CO_2. Information gathered from meetings with MCT staff, component drawings, and the bill of materials was analysed and a database of all significant components was produced. The mass of each was established along with the material breakdown and manufacturing processes for the component.

Information on the embodied energy and carbon content of materials and manufacturing processes was obtained from many sources including existing LCAs, journals, and textbooks published by recognized bodies. Where information on material breakdown and manufacturing process was not available, it was first assessed if this information would likely be significant. If so, further research was conducted and, when necessary, assumptions were made based on similar materials or components.

3.2 Raw materials

Figure 4 shows the most significant materials used in the manufacture of the Seagen turbine. Steel is used for most of the major components such as the 242 tonne (t) tower, the topside platform, and the crossbeam, which explains why it represents nearly 89 per cent of the 465 t total mass.

Data for material embodied energy and carbon are given in Table 2. It is primarily based on the Inventory of Carbon and Energy (ICE) [**18**], a database compiled by the University of Bath. The dataset offers a 'cradle-to-gate' assessment covering exploration and extraction of the raw and feedstock materials to the production of the processed material ready for collection at the factory gate. Its well-documented methodology is designed to ensure consistency and remove ambiguity through rigorous survey of secondary sources, and is derived, where possible, from UK sources. For this preliminary assessment it has been assumed that components possess embodied energy and CO_2 as though they were produced in the UK. Although many of the most significant components are produced outside of the UK, this is believed to be a reasonable approach. Cross-referencing of ICE data for steel products with European average data from the International Iron and Steel Institute [**22**] suggests that, if anything, the ICE data are more conservative (i.e. higher embodied values).

Data for materials not covered by the ICE have been sourced from elsewhere in the literature: technical journals, conference papers, and previous LCA studies, preferably accredited to ISO 14040. Embodied energy values for cast iron (used primarily in the gearboxes, hubs, and electrical components) were sourced from reference [**20**] and the embodied CO_2 was estimated based on the assumption that CO_2 emissions reflect the relative energy use between iron and steel. Around 9 t of composite material is used for the turbine rotor blades, crossbeam fairings (housing), and pod. The composites are manufactured from glass fibre, foam, and epoxy resin, with a small amount of carbon fibre used in the rotor blades. Ryyd and Sun [**19**] state embodied energy values for the composite material and provide an energy–CO_2 relationship to allow calculation of CO_2 emissions. Other data were sourced for epoxy resin and polyurethane foam filler [**21**].

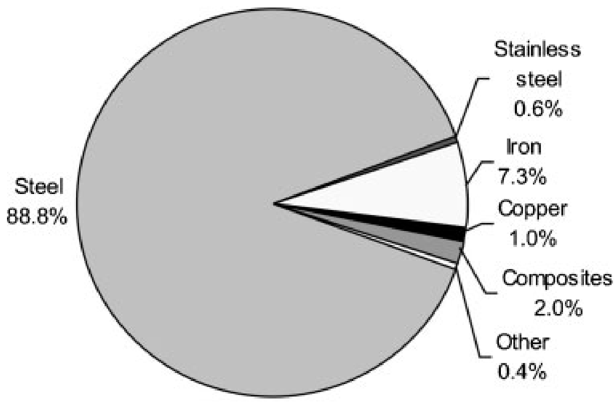

Fig. 4 Mass breakdown of Seagen turbine

Table 2 Summary of energy and CO_2 intensity of key materials [**18**], unless specified

Material	Embodied energy (MJ/kg)	Embodied CO_2 (kg CO_2/kg)
Aluminium (range: rolled – cast)	150.2–167.5	8.35–9.21
Carbon/glass fibre [**19**]	200.0	11.2
Cast iron [**20**]	37.0	3.3
Cement	2.35	0.28
Copper	55.0	4.38
Epoxy resin [**21**]	137.1	13.8
Nylon 6	120.5	5.5
Paint	80	6.1
Polyethylene/polypropylene	73.7	1.7
Polyurethane foam [**21**]	102.9	3.9
PVC pipe	67.5	2.5
Stainless steel	51.5	6.15
Steel (range: engineering – rolled plate)	11.7–45.4	0.68–3.19

3.3 Manufacturing

3.3.1 Manufacturing processes

The material life cycle inventory data specify 'cradle-to-gate' values that exclude downstream manufacturing processes. Where information on the downstream manufacturing processes was available (including painting and cathode protection) it has been included in the assessment, but data on some processes (e.g. forging) are not extensively documented and assumptions have been made. Table 3 summarizes the energy and CO_2 requirements for

Table 3 Embodied energy and CO_2 for selected manufacturing processes

Process	Energy input	CO_2 emissions
Composite pre-preg [**23**]	40 MJ/kg	4.78 kg CO_2/kg
Flame cutting [**24**]	8.5 MJ/m^2	1.015 kg CO_2/kg
Machining [**25**]	60 kJ/cm^3	0.15 g CO_2/cm^3
Sandblasting [**26**]	12.0 MJ/m^2	1.44 kg CO_2/m^2
Sand casting [**27**]	9.8 MJ/kg	1.172 kg CO_2/kg
Welding [**24**]	15.1 MJ/m	1.804 kg CO_2/m

selected manufacturing processes. The values for welding [**24**] relate to thinner plate used in ship building but the underestimate in energy and carbon terms is likely to be small. The effect of this and other manufacturing assumptions is examined in section 4.4.

3.3.2 Tower

The tower for the Seagen is manufactured in Denmark and shipped complete to the assembly site ready to be installed. The 54.6 m tall structure is fabricated from steel plates rolled and welded into circular sections. Stainless steel, cast iron, and galvanized steel sections complete the tower. The external surface above the sea bed and the entire internal surface is sand blasted, painted, and partially aluminium cathode protected.

3.3.3 Crossbeam

The crossbeam supports the rotors and consists of a 92 t fabricated steel structure, moulded composite fairings, and iron castings. The steel and iron components are corrosion protected. The composite crossbeam fairings, which cover the structure are assumed to be made using the pre-preg [**23**] process consisting of 70 per cent glass fibre, 5 per cent foam, and 25 per cent epoxy resin; the external surface is painted. It was assumed that 10 per cent of the composite material was wasted and disposed of in landfill; this is in line with LCA data for wind turbines [**10**].

3.3.4 Rotor blades and power train

The turbine had two power trains, each consisting of two rotor blades, hub, gearbox, generator, and frequency converter (Fig. 5). A single transformer (housed in the topside) connects them to the subsea cable. MCT supplied component masses and some manufacturing information, but the remaining components were assessed based on LCAs of similar devices. Each rotor blade was made up of 800 kg of composite material for the blade spar and skin together with a cast iron hub-connector. The blade composites had a similar composition and wastage to the crossbeam fairings. The hub assembly was mostly cast iron (machined and protected) along with two forged steel bearings. Each gearbox was made from a cast iron casing, forged steel gears and shaft, structural steel, and oil; an estimate of the breakdown was provided by MCT. Allowance was made for high-accuracy machining of the shaft and gears, but the minor contribution from heat treatment was omitted. LCAs for similar electrical components facilitated estimates for the 660 kW induction generators [**28**], frequency converters [**29**], distribution transformer [**30**], and the 22 kW induction motors controlling the blade pitch [**31**]. These components comprised mostly steel elements along with iron, copper, and aluminium.

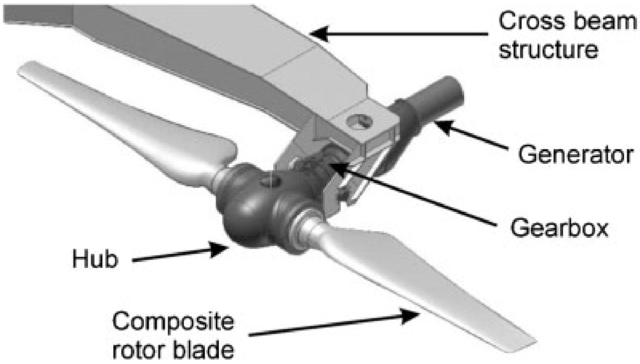

Fig. 5 Seagen power train

3.3.5 Manufacturing of the topside

The topside is the assembly that sits on top of the tower clear of the water. The 56 t assembly is mostly steel, housing the controls, electronics, and hydraulic systems, and a crane. A 1 t glass fibre pod curves round the topside steel fabrication and is manufactured in a similar manner to the crossbeam fairings. Three steel 'tea strainers' act as the tower's floors and house the steel control and electronics cabinets. LCA data for an industrial controller [**32**] were used to estimate the control and electronics footprint; this assumption will have negligible impact given the low mass of the control units. The hydraulic system allows the rotors and crossbeam to be raised for maintenance. MCT provided a partial component and weight breakdown: the twin 22 kW motors were modelled as per the blade pitch motors [**31**] and the remainder of the power pack (hydraulic pumps, bore valves, etc.) was assumed to be manufactured from general steel.

3.3.6 Cabling

A 500 m armoured multi-core cable connects the turbine to the distribution network. Each 107 mm^2 copper core is surrounded by 4.5 mm of crosslinked polyethylene (XLPE) insulation with the whole cable protected by 5 mm of steel armour wire and a

3.5 mm polypropylene sleeve. This material, along with 222 m of 394 mm^2 copper cable, is included in the assessment, but low voltage cabling has been omitted as the total mass was not significant.

3.4 Transportation and installation

The transportation stage of the life cycle required assessment of the fuel use and CO_2 emitted by vehicles transporting turbine components to the assembly and installation sites. The DEFRA guidelines for emissions reporting provide fuel consumption and emissions for most transport modes [**17**]. Emissions for other, more specialist shipping and vehicles were derived, where necessary, from product specifications. They assumed the use of diesel with embodied CO_2 of 2.63 kg CO_2/litre [**17**] and are presented in Table 4.

The turbine is preassembled prior to installation at the assembly site in Belfast, N. Ireland. For the 21 most significant components (~ 96 per cent of the total weight) the distance from the supplier to the assembly site was calculated. Most are transported by road but the tower, crossbeam, and another minor fabrication are transported 1520 km by cargo ship from Denmark. Some assemblies, e.g. the power train, are pre-tested elsewhere before delivery to Belfast; however, the assumption that each component is delivered direct to the assembly site is reasonable given the relatively small distances involved. On the basis of their size and weight, the other 18 most significant components were assumed to be transported by either a 28 t articulated lorry or a 10 t rigid lorry. The remaining 22 t of components were estimated to require the use of five rigid lorry loads (at 50 per cent loading) for the weighted average travel distance (811 km) of the 21 main components.

The installation procedure for the Seagen turbine is outlined in the company's Environmental Statement [**16**]. Components are assembled then transported as a number of main assemblies to the installation site at Strangford Lough Narrows, approximately 100 km from Belfast. The bulk of the components are transported to the installation site on a marine jack up platform, towed and positioned by two tugboats [**16**]. The remainder of the installation-related transport emissions come from a Multicat workboat (which carries the remaining components) and the use of a mobile crane and van (Table 4). The installation involves a 4 m diameter, 23 m deep hole being drilled into the seabed along with a 500 m-long directionally drilled tube for the sub-sea cable. The energy and CO_2 emissions from the drilling operations were estimated from the duration of the processes and relevant technical data sheets. The mobile crane was assumed to operate for around half of the working time at the site consuming fuel at around 9 litres/hour (McNally Crane Specialists, 2006, personal communication). In addition to the use of fuel, the installation also requires the use of a 26 t sacrificial steel shoe (drill bit left in the sea bed) and 75 t high-strength polymeric grout. The tugboats make a second return journey to collect the barge.

Table 4 Fuel consumption and CO_2 emissions associated with various transport modes

Transport mode	Fuel consumption litres/km	CO_2 emissions kg CO_2/km
Cargo ship (1000 t load)	14	36.82
Tug boat (40 t pull) [**33**]	16	42.08
Multicat (2000 bhp) [**34**]	8.5	22.35
Inspection vessel [**34**]	3.3	8.76
Fully laden articulated lorry [**17**]	0.448	1.17
100 t mobile crane (McNallys Crane Specialists, 2006, personal communication)	0.94	2.47

3.5 Operations and maintenance

The operations and maintenance schedule for the Seagen turbine, outlined by MCT, involves a six-monthly inspection cycle and the removal, inspection, and refurbishment of the power train on a five-yearly cycle. The six-monthly inspection will require the use of a boat to transport the inspection team and the hydraulic system provides the energy required to lift the crossbeam above the water surface. The five-yearly power train refurbishment requires a Multicat vessel and crane to swap the complete system for another. The embodied energy and CO_2 of replacement components such as bearings, gearbox oil, and paint are included in the analysis, but that of the entire replacement power train is not included as a spare power train can service an entire farm of Seagen turbines.

3.6 Decommissioning and disposal

While the decommissioning process for the Seagen turbine has not been considered in detail at present, it is expected to be largely a reversal of the installation procedure. The tower would be removed by cutting its circumference around 0.5 m below the seabed. The top section of the tower will be returned to land with the remaining 22.6 m left below the seabed. As the tower wall is thicker at the base the foundation represents 51 per cent of the tower mass, which could otherwise be recycled. The sub-sea cable can be left *in situ* or recovered for disposal or recycling; the latter is assumed here.

LCA studies for other renewable technologies demonstrate that the recycling stage of the life cycle have a significant impact on embodied energy and CO_2 [**10**, **11**, **13**]. By recycling material, the energy consumed and CO_2 produced through raw material extraction and primary processing can be avoided. The savings, which typically range from 60 per cent for steel up to 95 per cent for aluminium, can be credited to the life cycle and reduce overall energy and CO_2 intensities and paybacks. Allowable under ISO 14040 [**7**], a series of methodologies have been developed for the recycling of metals [**35**, **36**]. The key factor in determining the level of credit is the rate of recycling [**35**].

As Seagen has not yet been installed, scenarios for recycling and disposal were based on two assessments of large wind turbines produced by Vestas. The first [**10**] applied a conservative 90 per cent recycling scenario for steel to account for uncertainty, while the later study [**11**] assumed 100 per cent recycling. Given the level of uncertainty here, it has been assumed that 90 per cent of all steel components other than the tower are recycled with the data based on the same materials values from the ICE database [**18**]. With half of the tower remaining in the seabed following decommissioning, only 49 per cent of the steel tower mass is assumed to be recovered. All other recycling rates materials are based on reference [**10**], with rates of 90 per cent for iron, 95 per cent for copper with plastics and composites going to landfill.

4 RESULTS AND DISCUSSION

4.1 Energy consumption and CO_2 emissions

Figure 6 shows the respective embodied energy and CO_2 emissions for each of the life cycle stages for the Seagen turbine. The gross embodied energy (i.e. excluding the recycling credit) is 25 903 GJ, the most significant stage being the materials and manufacturing stage, which accounts for 86 per cent of gross energy consumption. The gross life cycle production of CO_2 is 1924 t with a similar proportion represented by materials and manufacturing.

The credit offered by recycling is significant with the 22 per cent credit lowering the net embodied energy by 5595 GJ to 20 308 GJ and the 26 per cent carbon credit lowering embodied CO_2 to 1418 t CO_2. The recycling credits are lower than the 30 per cent values for wind turbines [**11**], which is partly attributable to the conservative recycling rates assumed (typically 90 per cent) but is primarily a result of less than half of the tower being recovered and recycled. Should it be feasible to retrieve the entire tower and recycle 90 per cent of it, then the recycling credits would be raised to 35 per cent for energy and 42 per cent for CO_2. The impact of the

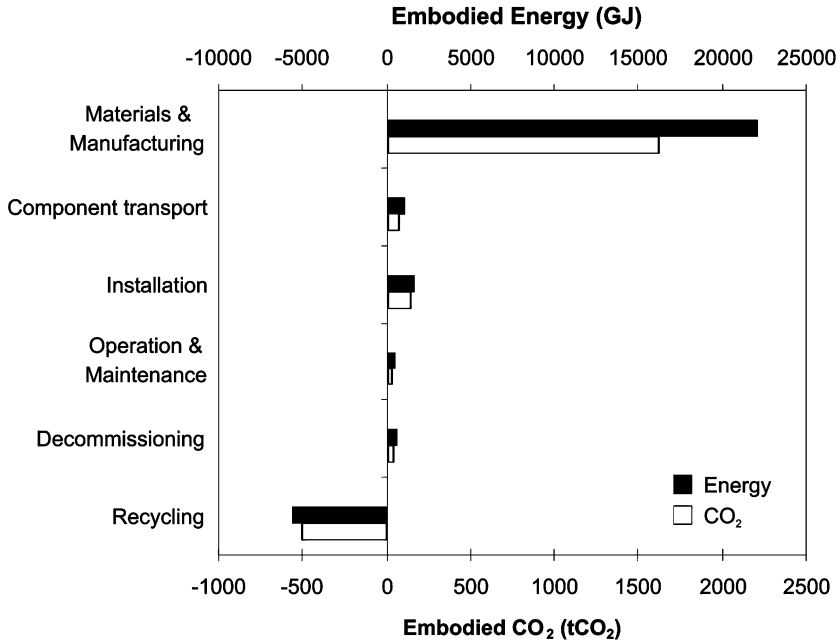

Fig. 6 Energy consumption and CO_2 emissions per life cycle stage

recycling credit is explored further in the sensitivity analysis in section 4.4.

Steel use is by far the main contributor to the overall embodied energy and CO_2 emissions, responsible for 68 per cent of the total gross energy consumption. It should be noted, however, that over 85 per cent of the total recycling credit comes from steel. Composite materials contribute disproportionately because, although representing only 2 per cent of the turbine mass, they are responsible for 9.4 per cent of embodied energy and 7.8 per cent of embodied CO_2. The use of diesel fuel, mainly for shipping, is also significant and represents around 15 per cent of net life cycle energy and CO_2.

4.2 Energy and carbon intensity

To allow comparisons to be made between Seagen and other electricity-generating technologies, the energy and CO_2 intensities, i.e. per unit of production, were calculated. This was done by dividing the overall embodied energy and CO_2 emissions by the total production of the turbine over its lifetime.

At the Strangford site, annual production of 4736 MWh equates to 94.7 GWh over the 20-year lifetime. Dividing the net life cycle energy consumption by the lifetime production indicates an energy intensity of 214 kJ/kWh. Similarly, the life cycle CO_2 emissions result in a carbon intensity of 15 g CO_2/kWh. Omission of the recycling credits raises the respective intensities to 273 kJ/kWh and 20 g CO_2/kWh. A discussion on how these values relate to other electrical generation technologies follows in section 4.3.

The performance of the device can also be measured by payback periods which indicate how quickly embodied energy and CO_2 are 'recovered' by the carbon-free energy produced by Seagen. The energy payback period is ascertained by dividing the lifetime energy input by the annual energy production

$$\text{Energy payback} = \frac{\text{Life cycle embodied energy}}{\text{Annual energy production}} \quad (1)$$

The energy payback is therefore around 14 months. Omission of the recycling credit from the calculation increases the payback period to just over 18 months. Similarly, the carbon payback can be ascertained by dividing the total embodied carbon by the annual carbon avoided by the use of the system as follows

$$CO_2 \text{ payback} = \frac{\text{Life cycle embodied } CO_2}{\text{Annual } CO_2 \text{ avoided}} \quad (2)$$

The carbon avoided by Seagen will depend on what generation is displaced and is time- and location-dependent. Despite this, it is accepted practice to use the average carbon intensity of grid electricity for the calculation of avoided CO_2 with the figure of 0.43 kg CO_2/kWh advised by DEFRA [**17**]. Use of this value suggests generation from Seagen avoids 2036 tCO_2 per year indicating a carbon payback period of just over 8 months. The omission of the recycling credit raises the payback period to 11 months.

4.3 Comparison with other sources of electricity

The carbon intensity of the Seagen marine current turbine can be compared with other forms of electricity-generation technology (Fig. 7). It is clear that the Seagen marine current turbine is a significant improvement on fossil fuel electrical generation and compares well with established renewable technologies. Its carbon intensity is significantly lower than that of solar photovoltaic cells and only slightly higher than the 9 g CO_2/kWh quoted for large wind turbines sited offshore [**12**]; similarly its energy payback period (14.6 months) is well within reach of the 8 months quoted for large wind turbines [**11**]. It should be noted that direct comparison with values from other LCA studies can be problematic, as the assumptions may be different and often non-conservative as well as issues regarding compliance with the ISO standards. Despite this, it is clear that given Seagen's relatively early stage of development the results are very encouraging.

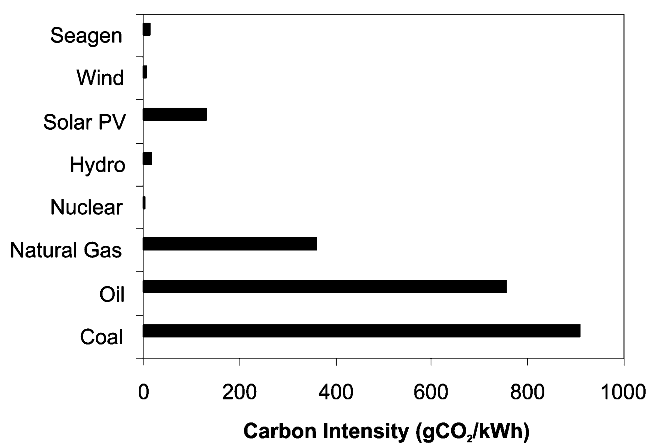

Fig. 7 Life cycle carbon intensities of energy generating technologies, after reference [**37**]

4.4 Sensitivity to assumptions

There are several potential sources of uncertainty in this study arising from non-availability of data. These include the omission of energy or CO_2 emissions associated with certain materials or processes or the assumptions made in response. These exclusions and assumptions have been justified earlier and are not expected to have an impact on the overall results of the analysis or the conclusions drawn. However, there were several factors that could materially affect the results. These include: production, design life, recycling rates, the embodied energy and CO_2 of the materials and manufacturing processes, and the installation location. The sensitivity of the environmental performance of Seagen to these factors was examined.

The assumed electrical energy produced by Seagen has a major impact on intensity and payback times as these vary by the same amount. A 10 per cent reduction in production raises carbon intensity to 16.6 g CO_2/kWh and energy intensity to 238 kJ/kWh; energy and carbon paybacks are lifted by around one and a half and one month, respectively. Relative changes in design life have a similar impact to production changes. The recycling rate for steel was conservatively assumed to be 90 per cent for non-tower components: lowering the rate by ten percentage points alters the performance indicators by around 4 per cent raising carbon intensity to 15.6 g CO_2/kWh, energy intensity to 222 kJ/kWh and carbon and energy paybacks by one month. Reducing the recovery rate for the tower by the same proportion suggests a further 2 per cent deterioration in performance.

The materials data from the ICE [**18**] used in this study are subject to uncertainty; typically ranges for energy values of ± 30 per cent are indicated. Extreme scenarios for high and low materials values were examined with the same ranges assumed to apply to carbon intensity. Application of the high materials values raised respective energy and carbon paybacks to 19 and 11 months and intensities to 281 kJ/kWh and 19.8 g CO_2/kWh. The low materials values gave an energy payback of 10 months and intensity of 147 kJ/kWh with a carbon intensity of 10.1 g CO_2/kWh and payback of 6 months. Typically, the payback and intensities change slightly more than the change in material value. Further work on the variance of material embodied energy and CO_2 would help greatly in reducing the uncertainty in device environmental performance.

Uncertainties in the materials and manufacturing stage relate to the embodied energy and CO_2 assumptions for the manufacturing processes (e.g. sand-blasting). Their influence was assessed by doubling the estimate of embodied energy and CO_2 for these processes. This resulted in increases of approximately 5 per cent in energy intensity (225 kJ/kWh) and 7 per cent in carbon intensity (16.0 g CO_2/kWh). This shows that any error in the data for the manufacturing processes falls well within acceptable tolerances.

Although the installation site is relatively close (50 km) to the assembly port, it is conceivable that other projects would be further away. As ships have high fuel consumption per unit distance relative to land transport (Table 4), and diesel fuel is shown to represent a significant amount of embodied energy and CO_2, the influence of shipping distances was investigated by doubling the distance travelled by vessels and other vehicles during installation, O&M, and dismantling. This resulted in increases in energy and carbon intensity of just under 8 per cent to 231 kJ/kWh and 16.1 g CO_2/kWh, respectively, showing a modest influence.

Overall, the sensitivity study shows that even under the most adverse scenario considered the environmental performance of the Seagen remains excellent and comparable with large commercial wind turbines.

4.5 Potential improvements

The current study has identified the materials, processes, and life cycle stages that contribute to energy consumption and CO_2 emissions. The information within it can be used by the manufacturers to assess improvements on environmental performance grounds alongside other factors such as cost, feasibility and aesthetics. To illustrate the potential for reduced environmental impact, several areas have been identified.

Steel is the major source of Seagen's embodied energy and CO_2, which is unsurprising given the benefits of using steel for large structures (e.g. strength, formability, and relatively low cost). While increased structural efficiency offers potential savings perhaps the major opportunity lies in capturing greater recycling credit through the recovery and recycling of the entire steel tower at decommissioning: recovery of the entire tower with 90 per cent recycling would lower energy and carbon paybacks to 11.9 months and 6.5 months, respectively, with intensities reduced to 179 kJ/kWh and 11.7 g CO_2/kWh. Alternative installation methods for the Seagen turbine, such as a short steel tower on a concrete seabed mount [**4**], may also offer greater energy and carbon efficiencies given the low embodied values for high-strength cement (Table 2).

Another opportunity to reduce environmental impact lies with the composites used in the turbine, given their disproportionate embodied energy and CO_2 and limited recycling possibilities. Replacement of composite components with less intensive materials may offer savings particularly for less performance-critical elements such as the topside pod.

5 CONCLUSION

This paper presents an analysis of the life cycle energy use and CO_2 emissions associated with the first installation of Seagen tidal current converters. It is shown that at 214 kJ/Wh and 15 g CO_2/kWh, the respective energy and carbon intensities are comparable with large wind turbines and very low relative to fossil-fuelled generation. The energy payback period is approximately 14 months and the CO_2 payback is around 8 months. The materials and manufacturing processes for Seagen are identified as the primary contributors to life cycle embodied energy carbon and improvements in the environmental impact of the Seagen can be achieved by increased material efficiency and alternative installation methods.

ACKNOWLEDGEMENTS

The authors are grateful for the assistance of staff at Marine Current Turbines Ltd for their prompt attention and enthusiasm. They also thank Nick Coleman in the Environment Group at Corus for his assistance with steel LCA data. This work was supported by the Scottish Funding Council through the Joint Research Institute in Energy with Heriot-Watt University as part of the Edinburgh Research Partnership.

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