

Net green energy potential of solar photovoltaic and wind energy generation systems

Jessica Daaboul^{a,*}, Patrick Moriarty^b, Damon Honnery^a

^a Department of Mechanical and Aerospace Engineering, Monash University, Clayton Campus, Victoria, 3800, Australia

^b Department of Design, Monash University, Caulfield Campus, Victoria, 3145, Australia

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ABSTRACT

“Green energy” is the energy that can be produced while sustaining ecosystem services. Maintenance of the services provided by the ecosystem requires energy, termed the ecosystem maintenance energy (ESME). Including ESME costs in energy accounting enables assessment of an energy plant’s ability to produce energy over and above inputs and EMSE costs over the lifetime of the plant. In this work, an assessment of the potential of two renewable energy plants wind and solar photovoltaic to produce “green energy” is undertaken, those were chosen due to their likely dominance of the future energy market. The assessment is done using a methodology that unifies environmental impact assessment, ESME and energy accounting into a single metric termed the green energy return on investment (EROI_g). The paper also extends ESME calculation by incorporating ecosystem impacts that were previously unaccounted-for such as: biodiversity loss; delayed ecosystem maintenance; carbon capture by photosynthesis; ozone depletion and formation and ionizing radiation. The solar and wind energy plants considered were sized to produce an equivalent amount of annual energy and were placed at a theoretical location where the capacity factor (CF) is equivalent to the average global utility scale CF for each resource. The study found that onshore wind energy has a greater potential in generating green energy with an EROI_g of 17.19. Removal of impacts related to biodiversity loss, which is included here for the first time, is found to play a critical role in plant assessment from both biodiversity and CO₂ capture by photosynthesis perspective. Plants needing and providing biodiversity offsets are shown to provide an overall 18%–25% improvement in EROI_g. This improvement is triggered by the corresponding CO₂ capture by photosynthesis. Some design options were evaluated to determine the sensitivity of the resulting EROI_g to the plant design and to the temporal element of the investigation. Those include the addition of battery storage and the delay in action on ecosystem maintenance from a 20-year to a 100-year time horizon which were found to reduce the resultant EROI_g by >40% and >87% respectively.

1. Introduction

Fossil fuels have sustained growth in global energy consumption for more than 150 years. Over this time the negative environmental impact of their use on the Earth’s ecosystem and the services it provides have become evident. Among these impacts, much attention has been given to the contributions their greenhouse gas emissions (GHG) have made to increasing global average atmospheric temperature (Ponce and Khan, 2021). The need to limit the GHG-driven increase in global average atmospheric temperature to less than 2 °C has been the subject of numerous reports by such organisations as the IPCC et al. (2022). Dominating the solutions to achieve this limit is a transition away from

fossil fuels to low-carbon emitting renewable energies (RE) (IEA, 2021). An additional consideration is the need to ensure that future energy systems maximise net energy (E_{net}) production while limiting GHG emissions (Connolly et al., 2016). For an energy system, E_{net} is often expressed as energy return on energy invested (EROI). Electricity generation from RE sources such as wind and solar PV have been shown to achieve reasonably high EROI whilst having minimal operational GHG emissions (Raugei et al., 2012). For this reason, they are considered key players in most future low carbon emission scenarios (Diesendorf and Elliston, 2018).

While minimising GHG emissions is important, environmental impacts extend beyond these alone (Sovacool et al., 2016). Those will vary

* Correspondence author.

E-mail address: jessica.daaboul@monash.edu (J. Daaboul).

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with technology type, plant scale, location, as well as the type and amount of materials used in the supply chain. Renewable energies are critical to future energy supply, hence the estimated scale at which they must operate is immense (Delina and Diesendorf, 2013) requiring significant quantities of materials and land area per unit of power produced (Pratiwi and Juerges, 2020). Therefore, the environmental impacts from non-GHG sources should be carefully considered when selecting a low impact RE technology for a specific location. Having lowest environmental impact requires clean-up of all the different toxins and addressing the impacts generated per kWh of energy production; this is known as ecosystem maintenance. Greater understanding is needed on which RE generation options have the highest net energy production and lowest overall environmental impact simultaneously (Sánchez-Zapata et al., 2016). Utilizing and expanding a method that enables this understanding is the focus of this work. Given their importance, attention is focused on large scale PV and on-shore wind systems.

Given the potential variation in environmental impact among RE plant types, selecting an energy generation plant on the basis of limiting environmental impact can be difficult. Consider the problem of evaluating two energy plants that produce the same net energy (E_{net}), but which have differing environmental impacts. If minimising GHG emissions (climate change impact) was the sole task, the selection is clear. However, if one has a large ecotoxicity impact but low climate change impact, whereas the other has low ecotoxicity impact but high climate change, impact selection becomes more complex. One solution is to evaluate energy plants via a metric that consolidates the different types of environmental impact into a single metric.

A number of approaches to consolidate impacts have been developed. For example, economic assessments based on Levelized Cost of Energy (LCOE), have been developed to include the monetary cost of energy externalities or environmental impact, in conjunction with the monetary cost of energy generation (Sovacool et al., 2016). However, LCOEs generally rely on approximations subject to variability based on estimates of willingness-to-pay, like market-based valuations, avoided cost, hedonic pricing and so on (Gaterell and McEvoy, 2005). LCOEs are also subject to market influences, particularly at low values of energy return on invested energy (EROI) (Hall et al., 2014).

Other methods link environmental impact to resource consumption, such as ecological footprinting (EF). Although powerful in communicating the environmental impact and reflecting humanity's use of resources in a single metric, methods such as this do not provide a means to account for the cost of environmental impact mitigation needed in energy policy. While a valuable tool, EF has been criticised for not being unable to provide sufficient information for a profound assessment of energy policy (Wiedmann and Barrett, 2010). As the goal here is to evaluate whether net energy can be produced after ecosystem maintenance, quantifying EF does not inform decision-makers on what energies and costs are involved in eliminating the identified problem and maintaining the ecosystem. To achieve this, a method that combines EF with energy accounting or transforms the outcomes of EF into a form that can be used in energy accounting is needed.

Other approaches to provide a unified assessment often rely on normalization of individual impacts that have typically been determined via Life Cycle Assessment (LCA). Through use of different normalization factors (or weights), individual impacts can be combined to produce grouped (class) metric or a singular unified impact metric. While helpful in enabling a comparative assessment outcome for competing technologies, the method is sensitive to the weights used, which may vary with technology, time and space. Weighting is generally based on certain emission patterns and environmental urgency associated with the timescale assessed. This sensitivity has led to this approach being labelled as subjective (Roesch et al., 2020). A further difficulty when assessing energy generation plants is the lack of a direct coupling between the resultant environmental impact and the need to maximise net energy production given limits in Earth's resources.

One approach to overcome these difficulties is to use as a starting point the link between energy production and environmental impact. Energy generation systems (polluters) should control their emissions, generated during their lifecycle (Recchini et al., 2019). Although control of environmental impact can be done via various means (Inumaru et al., 2021), energy will be needed to control emissions (Bridges et al., 2015) and for energy plants, this energy should come from the energy they produce. Moriarty and Honnery (2019) termed the energy needed to do this the ecosystem maintenance energy (ESME). This energy was first quantified by Daaboul et al. (2022) who allocated different impact source removal (ISR) methods to various environmental impacts. After accounting for ESME over the life of a plant, as well as the inputs required to construct, operate and decommission the plant, the ability of a generating plant to produce net energy, termed green energy, over its life can be undertaken. Similar to EROI, green energy assessment can yield a green energy return on energy invested, EROI_g (Moriarty and Honnery, 2019). Thus, unlike other methods, a plant's EROI_g provides in a single metric an objective measure of a generating plant's ability to produce net energy whilst maintaining the Earth's ecosystem.

Use of EROI_g as an indicator has been discussed by Moriarty and Honnery (2019), but is yet to be fully explored. While the ESME quantification methodology has been laid out (Daaboul et al., 2022), many lifecycle environmental impacts have yet to be addressed. Further, this method has not yet been applied to large-scale energy generation systems that are likely to dominate future energy production such as wind and solar PV. The principle behind the method as shown in Fig. 1, is to estimate the energy required to remove environmental impacts using ISR techniques (Daaboul et al., 2022). Environmental impacts are determined by undertaking an LCA of the energy generation plant. ESME is calculated as the sum of the energy required to operate all ISRs sufficient to remove impacts at either their source or at their point of impact. In this way, the energy required to remove the plant's environmental impacts can be directly accounted for as an input cost when calculating the energy plant's energy flows, and so EROI_g. If EROI_g is less than unity the system is unsustainable.

Use of ISRs effectively provides an energetic equivalence of an environmental impact. Thus, energy (Joules) becomes the quantity by which environmental impacts can be unified and combined with net energy analysis. While the energy needs of an ISR can be determined objectively, the ISR must be selected and a basis for selection among competing options, if any, must be agreed—justifications for choices made are detailed in section 2 of this paper. It is possible that significant development may be expected to occur with the technologies underpinning ISRs over the life of a plant, and so their energy needs may vary over time. Provided the objective remains to remove an impact using the ISR with the least ESME cost, technological improvement should lead to increasing EROI_g, *ceteris paribus*. As will be shown in section 5 of this paper, the location of the ISR in the plant life cycle is a critical aspect of ESME minimisation.

Fig. 1 outlines the lifecycle impacts previously considered in ESME calculations (Daaboul et al., 2022), but many significant additional environmental impacts must be included in order to fully assess the environmental impact of an energy system. Additional impacts include: biodiversity loss; temporal impact of delayed ecosystem maintenance; carbon capture opportunity by photosynthesis; ozone depletion and formation; particulate matter formation; ionizing radiation, and so on. This paper extends the ESME methodology (see Fig. 1) by quantifying the ESME cost of these additional emissions/impacts, thus allowing a more complete assessment of an energy plant's net green energy potential. A significant component in the assessment with substantial outcome is the quantification of ESME cost associated with biodiversity loss through the inclusion of biodiversity offsets. The importance of those was acknowledged at the 15th United Nation's Convention on Biological Diversity (COP-15). The quantification method used is based on the polluter pays approach that assumes energy generation plants clean up their emissions by investing energy in ecosystem maintenance.

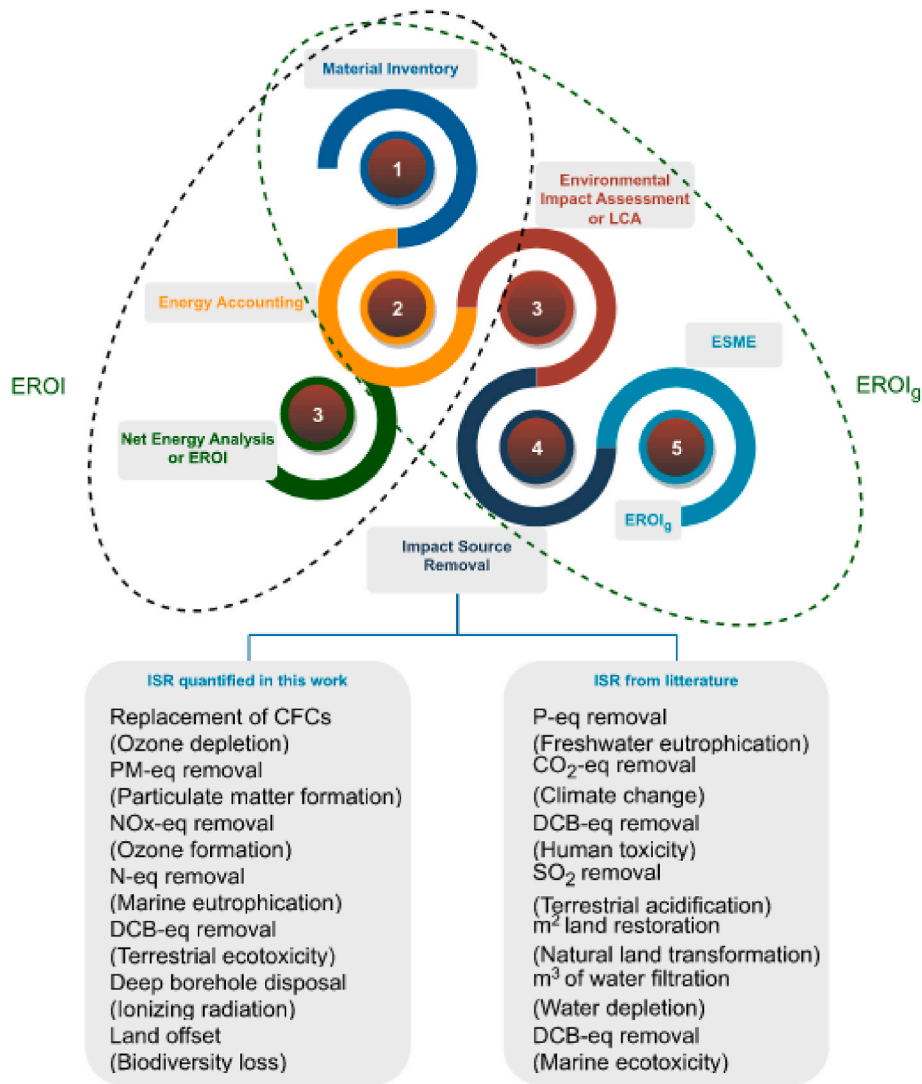


Fig. 1. The steps involved in EROI and EROI_g accounting (Daaboul et al., 2022). Diagram construction software (JGraph, 2022).

The evaluation of solar PV and wind energy generation technologies is a major component of this study. While renewables are proposed as solutions to the global energy-environment crisis, identification of the superior technology from energy/environment standpoint is necessary. This work evaluates the net green energy of solar PV and wind energy enabling a scaling of the capability of those technologies. Using the EROI_g methodology, the net green energy (E_{netg}) and EROI_g for a 50 MW onshore wind farm and a 100 MW solar photovoltaic (PV) are examined. The energy plants assessed are designed to achieve the same annual energy generation and are assumed to be in a location where the capacity factors (CF) of the solar and wind resources are equivalent to the average global utility scale CF. These energy sources were chosen as case studies because wind and solar energy generation are projected to grow significantly by the year 2050 (BP, 2022). Finally, a design options analysis is performed to study the impact of a renewable supply chain, battery back-up, and delayed action in ecosystem maintenance on EROI_g.

2. Methods

ESME cost is quantified as the sum of energies needed to remove the sources of environmental impact produced by an energy generation plant during its lifecycle (Daaboul et al., 2022). An ISR is allocated to every impact type based on its impact category determined by LCA (see

Fig. 1 and refer to Table 1). In assigning an ISR, the method distinguishes between.

- direct emissions (e.g. at the stack of the power plant or manufacturing facility);
- embodied emissions; and
- delayed removal of impact sources.

Early intervention for capture of contaminants provides the opportunity of reduced ESME (Raganati et al., 2014). One example of this can be the removal of CO₂ directly from a concentrated source in the plant stack, rather than delayed removal from a dilute atmospheric source by methods like Direct Air Capture (DAC) (Lackner and Brennan, 2009). The operational energy per unit impact quantity (e_i) is assigned to the ISR for each elementary lifecycle impact (I_i) per unit of gross energy produced (E_{gross}). The ISRs and their corresponding value of e_i for the impacts previously assigned in Daaboul et al. (2022) are shown in Table 1. The ESME_{*i*} for each ISR is then calculated and summed to give the total ESME,

$$\text{ESME}_i = e_i \times I_i \times E_{\text{gross}} \quad (\text{eq. 1})$$

$$\text{ESME} = \sum \text{ESME}_i \quad (\text{eq. 2})$$

ESME is then included as an energy cost in EROI in order to compute

Table 1
Measures required to control environmental impact.

Impact Category	Impact Type I_i	Impact Units	Impact Source Removal Process ISR_i	Energetic Equivalence e_i
Atmosphere	Climate change I_{GHG-d}	kg CO ₂ -eq/kWh	Direct Air Capture (DAC) and stack carbon capture.	Embodied emissions 2.44kWh/kg CO ₂ -eq ^a Operational emissions 0.49kWh/kg CO ₂ -eq ^a 1163.9kWh/kg ref
	Stratospheric ozone depletion - I_{CFC}	kg CFC11-eq/kWh	Replacement with R744 refrigerants	
	Particulate matter formation - I_{PM}	kg PM2.5-eq/kWh	Partially via the removal of SO _x and NO _x and partially via non-thermal plasma corona radical shower synthesis	66.9kWh/kg PM2.5 eq (50% captured by other processes)
	Loss of carbon capture opportunity I_{GHG-DL}	m ² /kWh	CO ₂ removal by DAC. Quantity of CO ₂ is based on 55 kgCO ₂ /m ² /y CO ₂ photosynthesis rate.	2.44kWh/kg CO ₂ -eq
	CO ₂ capture by offset land - I_{GHG-B}	m ² /kWh	CO ₂ removal by DAC. Quantity of CO ₂ is based on 55 kgCO ₂ /m ² /y CO ₂ photosynthesis rate.	2.44kWh/kg CO ₂ -eq
	Ozone formation human health - I_{NOx-H}	kg NO _x -eq/kWh	De-nitrification	8kWh/kg NO _x -eq
	Ozone formation, terrestrial ecosystem - I_{NOx-T}	kg NO _x -eq/kWh	De-nitrification	8kWh/kg NO _x -eq
	Marine Eutrophication - I_N	kg N-eq/kWh	Packed tower aeration water treatment	0.10kWh/kg N eq
	Freshwater ecotoxicity - I_{DB-FE}	kg 1,4-DB/kWh	Packed tower aeration water treatment	1.67kWh/kg DB eq
	Freshwater eutrophication - I_P	kg P eq/kWh	Packed tower aeration water treatment	3.33kWh/kg P eq ^a
Aquatic Environment	Marine ecotoxicity I_{DB-ME}	kg 1,4-DB/kWh	Packed tower aeration water treatment	1.67kWh/kg DB eq ^a
	Human toxicity - I_{DB-HE}	kg 1,4-DB/kWh	Foundry sand thermal reclamation	0.22kWh/kg DB eq
			Packed tower aeration water treatment	1.67kWh/kg DB eq ^a
			Foundry sand thermal reclamation	0.22kWh/kg DB eq
Terrestrial	Terrestrial ecotoxicity - I_{DB-TE}	kg 1,4-DB/kWh	Packed tower aeration water treatment	1.67kWh/kg DB eq ^a
			Foundry sand thermal reclamation	0.22kWh/kg DB eq
Land	Terrestrial acidification - I_{DB-FE}	kg SO ₂ -eq/kWh	Non-thermal plasma corona radical shower synthesis of SO ₂	0.11kWh/kg SO ₂ eq ^a
	Ionizing radiation I_{Bq}	kBq Co-60-eq/kWh	Land preparation - Deep borehole disposal	3.56E-1 kWh/kBq
	Natural land transformation L_R	m ² crop-eq/kWh refer to Table 3	Land preparation for plantation or rehabilitation	0.16kWh/m ² ^a
	Biodiversity loss L_B	m ² /kWh	Land offset and preparation for plantation or rehabilitation.	1 m ² /m ² for <50% soil sealing
			Bavarian metric with <50% soil sealing or >50% soil sealing.	3 m ² /m ² for >50% soil sealing
Water use	Water depletion - I_{WD}	m ³ /kWh	Desalination	6kWh/m ³ ^a

^a Values adopted from Daaboul et al. (2022).

EROI_g,

$$EROI = \frac{E_{out}}{E_c} \quad (\text{eq. 3})$$

$$EROI_g = \frac{E_{out}}{(E_c + ESME)} \quad (\text{eq. 3a})$$

$$E_{net} = E_{out} - E_c \quad (\text{eq. 4})$$

$$E_{netg} = E_{out} - ESME - E_c \quad (\text{eq. 4a})$$

Where E_{out} is the plant's secondary energy net output to society (plant's gross output less plant's self-use in operation), and E_c is the input of energy flow from other energy systems involved in extraction, construction, operation, and decommissioning. For the RE plants assessed here, self-use of energy during plant operation is assumed small so that $E_{out} = E_{gross}$. Net energy produced is given by E_{net} , and net green energy production is given by E_{netg} . In the EROI computation, this paper adopts the Hall et al. (2014) 'direct equivalent' method when applied to RE systems, this gives a 1:1 equivalence between electricity and primary energy. For the energy system to have positive E_{netg} potential the system is expected to have an $EROI_g > 1$ (Daaboul et al., 2022). In order to capture a wider range of environmental impacts than previously examined (see Fig. 1), the range of impacts included in the ESME calculation is expanded in this work using the same assumptions and methodology as detailed in the earlier paper.

2.1. Methods - marine eutrophication

Marine eutrophication belongs to the Aquatic Environment category. It is caused by excessive nutrient pollution in waterways or nutrient enrichment compounds such as of phosphorus and nitrogen (U.S. EPA, 2009). Removal of P-compounds can be done via packed tower aeration water treatment (Daaboul et al., 2022). As N-equivalent compounds are

under the aquatic environment category, their ISR process is assumed to be the same as the P-compounds. Packed tower aeration is stated to be effective in N-compounds removal (Jermakka et al., 2015). Concentration of nitrogen compounds in wastewater varies, based on the type and source of wastewater; this was reported to range between 51.9 mg/dm³ and 139 mg/dm³ in raw wastewater (Suchowska-Kisielewicz et al., 2018). Industrial wastewater was reported to contain >200 mg/L (Bawiec, 2019; Ghafari et al., 2008). The equivalent energy consumption at this concentration would therefore be: 0.1kWh/kg N-eq.

2.2. Methods – particulate matter formation

Particulate matter belongs to the Atmosphere category. Its ISR is split equally between removal via corona radical shower synthesis and as a by-product of the removal of SO_x and NO_x. As removal of PM via non-thermal plasma corona radical shower synthesis occurs at an intensity of 14.93g(PM)/kWh (Guo et al., 2020), this process would therefore consume 66.9kWh/kg.

2.3. Methods – ionizing radiation

Ionizing radiation causes major damage to humans and microorganisms (Videvall et al., 2022). Energetic impact associated with radioactive waste can be estimated by evaluating the energy associated with its continued safe containment using methods like deep borehole disposal (Bracke et al., 2019). Deep borehole disposal of nuclear waste is reported to occur in pre-set container sizes; a typically used container has a diameter of around 0.25m, mass up to 1900 kg, and is located at a depth of approximately 2500m (Beswick et al., 2014). Energy consumption for drilling of geothermal wells to a depth of 2500m consumes approximately 1.3E6kWh (Legarth and Saadat, 2005). If the concentration of transuranic wastes was considered representative of general radioactive waste, 3.7kBq/g could be assumed (Siegel and Bryan, 2014). This would indicate an approximate energy requirement of

0.36kWh/kBq.

2.4. Methods – ozone depletion

Ozone depletion is in the Atmosphere category. It originates mainly from the introduction of CFCs into the environment (EEAP, 2018). As the existing ISR methods in the Atmosphere category are not effective in removing CFCs, alternative approaches are taken. One approach is to substitute CFC sources with non-CFC refrigerants. The energy required to substitute those refrigerants and cooling units with an equivalent mass of benign refrigerants (e.g. C744) is taken to be the equivalent of the ISR energy. Refrigerant and AC unit manufacturing data were based on Weckert (2008) with linear scale-up. The energy required to produce 1 kg of C744 is taken to be 0.76kWh. The energy required to replace the AC system and accommodate the C744 refrigerant is 1163.14kWh/kg based on a linear scale up of the data in (Weckert, 2008). A total of 1163.9kWh/kg refrigerant is assumed.

2.5. Methods – toxicity

Toxicity is in the Aquatic Environment and Terrestrial categories. It originates from the introduction of 1,4-DCB-eq into the environment. These products are mostly generated by metals and minerals processing and tailings. The original EROIg methodology (Daaboul et al., 2022) proposed treating toxicity's impact sources with packed tower aeration. Whilst this treatment option is also adopted here in the computation of delayed ecosystem maintenance (section 5.3), early intervention allows the removal of those impact sources in a more energy-efficient way. Removal of toxicity impacts at the source can be done by thermal reclamation and reuse of foundry sands. This process consumes approximately 0.22kWh/kg (Ghormley et al., 2020). Assuming a 1:1 sand to 1,4-DCB ratio, the ISR's e_i becomes 0.22kWh/kg 1,4-DCB-eq.

2.6. Methods – biodiversity loss

Biodiversity loss could be caused by toxicity and land use change leading to disturbance of corresponding natural environment or habitat (Allan et al., 2013). As the toxicity component is addressed under the Terrestrial and Aquatic environment categories, only land use impact is considered here. Land use impact can be addressed by assuming that the disturbed natural habitat is established at another location to ensure continuity of biodiversity. This is known as biodiversity offset. The energy required can be quantified by combining biodiversity offset metrics such as the Bavarian Standard metric or DEFRA metric (Rayment et al., 2014) with land restoration energy consumption estimates. Critical to this is establishing the status of the existing land to be used by the plant (refer to Table 2 and Table 3) and any status of land used for biodiversity offset. Land status can be assessed by indicators such as the biodiversity intactness index used in planetary boundaries (Newbold et al., 2016), biodiversity hotspots, intact forest landscapes (Potapov et al., 2008), or vegetation health indexes (NOAA STAR Center for Satellite Applications and Research, 2018). Biodiversity land offsets are associated with the operation phase of the plant and are required until the direct land (L_D in Table 2) rehabilitation takes place at the end of life. Table 2 shows the amount of biodiversity land offset required based on land status and a biodiversity offset factor (F_{bio}). Table 3 shows the different types of land use and impact and the associated biodiversity offset requirements.

The biodiversity offset land area requirement is determined based on the plant's direct land (L_D) and on the land use changes in the indirect land (L_I) – refer to Table 3 for definitions. Soil sealing is chosen based on the status of existing land and its permeability.

$$L_B = L_D F_{bio} + L_{I(\Delta L)} F_{bio}$$

Where $L_{I(\Delta L)}$ is the portion of land undergoing changes in the indirect land. F_{bio} is determined in accordance with Table 2.

Table 2

Biodiversity offset requirements in the Bavarian method. From: DG Environment: Study on specific design elements of biodiversity offsets (Rayment et al., 2014).

Land types, descriptions and offsets required
Operation Phase: Direct Land L_D - Land disturbed for the construction and operation of the plant. For solar and wind plants it includes supporting system pads, turbines and panels, areas shaded by panels, access roads, substations, service buildings, and infrastructure. - Biodiversity offset land required during plant life. - Land requires rehabilitation at the end of life. Operation Phase: Indirect land L_I - Land used for the footprint of the project excluding direct land L_D. This area is occupied by the plant and is required for plant operation but may not be greatly impacted by the plant operation. - Biodiversity offset land required only when this area is being altered for the plant operation, e.g. Removal of existing trees to improve inflow conditions in the case of wind turbines. The altered portion of this area $L_{I(\Delta L)}$ requires biodiversity offset. - Impacted/altered part of this land requires rehabilitation at end of life only when this area is being altered for the plant operation. Operation Phase: Biodiversity offset land L_B - The amount of land required to offset the biodiversity impacts of direct land L_D and altered portion of indirect land L_I. - Biodiversity offset land area required depends on the significance of land prior to plant installation, e.g.: low significance for arable land; medium significance for forests with non-native species, etc (see Table 2). - Soil sealing: soil sealing affects soil functions, thus larger compensation area required in the case of high soil sealing. Rehabilitated Land L_{LR} - The transformed land requiring rehabilitation and its associated ESME are determined from the LCA. The LCA provides land transformation and land occupation data. Only the land transformation component of L_{LR} and L_T will be used in ESME computation. This is because the plant's land occupation is addressed in L_B via biodiversity offsets and the occupation of embodied land is assumed belonging to the boundary of the source process operation phase. Embodied land L_E - This is the transformed land embodied in the plant's supply chain spanning from mining of materials to end of life, it is associated with the material and energy flows. This is calculated directly from the lifecycle analysis (m^2 a crop eq/kWh). It is based on the relative species loss; species richness; recovery time (years) for species richness of the affected lands in the supply chain. This is derived from the following components in LCA: land transformation and land occupation. L_E includes embodied land in the supply chain or lifecycle of the plant.

Table 3

Land areas and biodiversity offset.

Factors affecting offset	Biodiversity offset factor - F_{bio}	
	>50% Soil sealing	<50% Soil sealing
Low Significance (I) – intensively used arable land species-poor grassland, canalised water courses, biodiversity-poor agricultural or amenity landscapes, etc	0.3–0.6	0.2–0.5
Medium Significance (II) – forest with non-local/non-native species, individual trees tree groups or hedges without high biodiversity interest, extensively used grassland, floodplain habitats, etc	0.1–1	0.5–0.8 (0.2 For intensively used grassland)
High Significance (III) – mature semi-natural forest with a high proportion of locally appropriate tree species, mature species-rich hedgerows, copses and woodland edges, natural or near-natural freshwater landscapes, culturally significant landscapes, etc	1–3 (Or higher in exceptional cases)	1–3 (Or higher in exceptional cases)

2.7. Methods – net carbon capture from land use change

The rise in vegetative cover on land required to achieve the biodiversity offsets provides the prospect for carbon capture. Additionally, large scale removal of existing vegetation from the land directly used by the plant (the plant's direct land L_D - see Table 3) reduces the opportunity of carbon capture by photosynthesis. These GHG capture prospects and reductions must be included in any assessment of the GHG impacts. Changes in CO_2 capture via these two sources are summed over the life of the plant from construction to land rehabilitation following plant decommission.

Combining CO_2 capture through this process with the reduced CO_2 capture by the plant's direct land gives the net GHG capture based on land use changes,

$$GHG_{\Delta L} = I_{GHG-DL} L_D - I_{GHG-B} L_B \quad (\text{eq. 5})$$

Where I_{GHG-DL} ($kgCO_2/m^2$) is the loss of CO_2 capture by the direct land L_D , and I_{GHG-B} ($kgCO_2/m^2$) is the carbon capture prospect at the biodiversity offset land L_B .

While vegetation cover varies from region to region, an annual carbon capture rate of 55.0 ($kgCO_2/m^2$) is typical of many vegetation types (Billings et al., 1966; Ludlow and Wilson, 1971). As a simplification, this value is used for both direct and biodiversity offset land over the life of the plant, $I_{GHG-DL} = I_{GHG-B}$. The sensitivity to direct land vegetation cover (carbon capture rate) is examined in section 4.2.

2.8. Methods – total greenhouse gas emission capture

Greenhouse gas emission capture is required for GHGs directly emitted by the plant, which are captured at the stack, and those indirectly emitted throughout the plant's lifecycle made up of embodied emissions and those resulting from changes in land use. All indirect emissions are captured from the atmosphere.

For the direct emissions from the plant, given by I_{GHG-d} ($kgCO_2\text{-eq/kWh}$), ESME is given by,

$$ESME_{GHG-d} = e_{GHG-d} I_{GHG-d} E_{\text{gross}} \quad (\text{eq. 6})$$

Where e_{GHG-d} ($kWh/kgCO_2\text{-eq}$) is the energy required to operate the direct GHG emission ISR, see Table 1. This may be operated at the plant, or located in the supply chain, this is discussed below.

DAC is assumed for the removal of all indirect emissions. DAC energy requirement is given by e_{GHG-e} ($kWh/kgCO_2\text{-eq}$). Indirect emissions are made up of those embodied in the plant and supply chain, I_{GHG-e} ($kgCO_2\text{-eq/kWh}$), and those resulting from land use change $GHG_{\Delta L}$ ($kgCO_2$). Indirect GHG emissions ESME is calculated by:

$$ESME_{GHG-I} = ESME_{GHG-e} + ESME_{\Delta L} \quad (\text{eq. 7})$$

Where

$$ESME_{GHG-e} = e_{GHG-e} I_{GHG-e} E_{\text{gross}} \quad (\text{eq. 8})$$

$$ESME_{\Delta L} = e_{GHG-e} GHG_{\Delta L} \quad (\text{eq. 9})$$

$$GHG_{\Delta L} = (I_{GHG-DL} L_D) - (I_{GHG-B} L_B) \quad (\text{eq. 9a})$$

Total GHG emission ESME is given by,

$$ESME_{GHG} = ESME_{GHG-d} + ESME_{GHG-I} \geq 0 \quad (\text{eq. 10})$$

A requirement for $ESME_{GHG}$ to be larger than or equal to zero is imposed to avoid impact trading such that greater removal of one impact cannot be used to justify reduced removal of a different impact. A further constraint is that while any excess reduction of an environmental impact by the plant or its biodiversity offset acts to neutralize similar impacts created by other sources of pollution (eg. other energy generation plants), the ESME associated with this sits outside the plant's boundaries.

3. Calculation

3.1. Calculation – facilities assessed

The developed ESME assessment and EROIg methodology is used to assess the performance of a hypothetical 50 MW wind farm and a solar photovoltaic (PV) array that generates an equivalent amount of annual energy. This size was chosen to remove the non-linearity that occurs with scale-up from smaller plants. Both systems are located in an assumed location where the capacity factors (CF) of the solar and wind resources are equivalent to the average global utility scale CF for each resource. This was chosen to remove any bias associated with spatial characteristics, location, and country specific energy mix. Based on year 2019 data as reference, the global utility scale onshore wind average CF is 36% and 18% for solar PV (IRENA, 2022). At these capacity factors and assuming 10% average annual energy loss due to curtailment, a 50 MW wind plant and a 100 MW solar farm would each produce a theoretical 142GWh/y. The wind farm comprises 25 onshore turbines of 2 MW capacity each. Characteristics of these turbines are as reported in the Ecoinvent library and are based on VESTAS V80 data from the year 2004. The solar PV plant consists of approximately 500,000 m^2 of mono Si cell type ground mounted panels with approximately 200W/ m^2 capacity each; the characteristics of the plant are based on IEA's lifecycle inventories report (Frischknecht et al., 2020).

The wind farm is assumed to have a 20-year life and the PV farm a 30-year life. While the longer lifetime of the PV yields a higher lifetime gross energy, performance is based on a per kWh basis. This difference in plant lifetime also affects the options analysis in this work (section 5.1) when the impact of adding batteries to the systems is assessed. Major materials such as wind turbines, solar panels, mounting system/shafts, electric cables, and power systems are assumed to travel 10,000 km by sea and 100 km by land. Given the similarity of the plant outputs, the transmission network and network large scale transformers are excluded from the LCA. This enables calculation of the final stage electricity originating from the plants. The EROI of final stage electricity originating from renewables is reported in the literature to be 5.9 for Mono-c Si solar PV systems (Raugei et al., 2012) and 25.2 for wind systems (Kubiszewski et al., 2010).

3.1.1. Land requirements

Land requirements assumed for the wind farm (Denholm et al., 2009) are 1.0 ha/MW for the direct land L_D and 34 ha/MW for the total site area on average (this is the direct and indirect land ($L_D + L_I$)). Using these, the wind farms requires approximately 50 ha for direct land L_D and 1700 ha of total site area. The indirect land L_I remains untouched throughout the lifecycle of the plant, whereas the direct land L_D is assumed to be transformed into land status similar to roads. For the wind farm LCA, the existing vegetation cover for both direct and indirect land (L_D and L_I) is assumed to be grassland (refer to Section 3.2).

Land requirements assumed for the solar farm (IRENA, 2022) are 1.9 ha/MW for the total land. Site area is assumed to be transformed from grassland into urban discontinuous structures, with 30% of that land to be used for roads. Based on this, a 100 MW solar farm will occupy a land of approximately 190 ha. All land used for the solar plant is classified as direct.

In the creation of biodiversity offset lands, this study assumes that damaged lands used formerly as industrial or mine sites are proposed to be reclaimed, rehabilitated and vegetated. Biodiversity offset carbon capture prospects are computed based on 100% of the offset land being covered with vegetation. The contribution of particulate matter removal by vegetation in the offset land is small and has not been included in this assessment.

3.2. Calculation – lifecycle assessment

The LCA modelling approach followed in this work is process-based

Table 4
LCA scope, units, and boundaries.

Process	100 MW PV array	50 MW Wind farm
Goal and scope	To inform the computation of EROI _g of PV generated electricity.	To inform the computation of EROI _g of wind generated electricity.
Audience	Scholars and policy makers	Scholars and policy makers
Functional unit	Generation of 1kWh of average PV electricity	Generation of 1kWh of average wind electricity
System boundary	Solar PV system including: Single-Si modules Mounting system Site cabling Diesel for construction Electricity for modules installation Tap water for panels washing Inverter	Wind turbines including: Rotor & Nacelle Electronics Site cabling Tower Foundation Diesel for construction & maintenance Electricity for excavation and installation Turbine transformer
Excluded elements	Transformation and power grid as these elements are common for both plants	Transformation and power grid as these elements are common for both plants
LCA boundary	Raw material extraction Manufacturing Plant transport (Chinese source) Installation Operation Washing/maintenance Decommissioning End of life/waste	Raw material extraction Manufacturing Plant transport (German source) Installation Operation Transport/maintenance Decommissioning End of life/waste
Spatial boundaries	Global material inputs. Chinese PV source – for manufacturing grid mix purposes.	Global material inputs. German turbine – for manufacturing grid mix purposes.
Temporal boundary	PV lifespan of 30 years	Turbine lifespan of 20 years

and associated with the attributional approach to allocation of impacts. The impact allocation at point-of-substitution approach is used in order to ensure the end product carries burdens from the products chosen in their supply chain. The LCA was conducted using the Ecoinvent V3.5 LCI database. In accordance with the LCA framework in ISO 14040 for LCA, LCA data is disclosed in Table 4.

The ReCiPe Midpoint Europe Individualist (I) impact assessment method and the Cumulative Energy Demand (CED) methods were used to generate the lifecycle impact in both studies. The Individualist (I) cultural perspective is chosen as the study proposes methods for the power plant to clean up its own emissions; major emissions therefore are not expected to reside in the environment for longer than 20 years. It therefore assumes an optimistic human adaptation and proactiveness in time or the expectation that proper management can avoid future damages. The results of the LCA for wind and solar PV units respectively are shown in Table 5. The midpoint level of impact categories is chosen due to the need for identifying quantities of impact source.

4. Results

Table 5 shows the EROI and EROI_g results of wind and solar plants along with the midpoint level LCA indicators and corresponding ESME_i energy. The resultant EROI is 6.13 for the PV plant and 23.7 for the wind farm. EROI_g for the PV plant is 3.59, and 17.19 for the wind farm. Both technologies have $E_{netg} > 0$ with E_{net} for wind produced electricity higher than that of solar PV. Net energy E_{net} per unit gross energy for the wind plant is 0.96kWh/kWh while the net green energy E_{netg} per unit gross energy is 0.94kWh/kWh; for the PV plant, $E_{net}/E_{gross} = 0.84kWh/kWh$ and $E_{netg}/E_{gross} = 0.72kWh/kWh$.

As used in Table 5, $\%E_{net}$ is defined as the share of net energy produced by 1.0kWh of gross energy generated. This is a percentage value representing net energy versus gross energy produced.

$\%E_{netg}$ is defined as the share of net green energy produced by 1.0kWh of gross energy generated. This is a percentage value representing net green energy versus gross energy produced. This metric indicates the impact of including ESME in the net energy assessment of different energy generation options.

4.1. Results - largest ESME costs

The highest ESME is expected to be for the PV technology indicating a higher overall environmental impact. For this plant, the largest elementary ESME_i energy consumption is associated with the Global Warming and Ecotoxicity impacts. For Global Warming, LCA results indicate that this is mostly due to iron production, heat required in manufacturing, electricity, glass, copper, aluminium, and silicon production in addition to transport. For the Ecotoxicity impact, this is mainly due to the production of wafers, copper, zinc, nickel and steel.

4.2. Results - land use and carbon capture

As shown in Table 5, carbon captured by the vegetation in the biodiversity offset land (eq. (5)), and resultant GHG_{ΔL} is significant. The captured carbon acts like a carbon offset because the added vegetation behaves as a carbon sink. The amount of GHG_{ΔL} however is sensitive to the status of existing land and vegetation type on the RE plant site driving the need for biodiversity offset. Given the large impact of GHG_{ΔL} on the plant's EROI_g and the varying amount of both biodiversity offset required and GHG_{ΔL} with land use type, the sensitivity of EROI_g to different types of land use is now examined.

Case 1. Existing site: Vegetated land; Offset prospects: no biodiversity offset

The plant is mounted on vegetated land, and no biodiversity offset was proposed (the ESME (gain) associated with this offset is ignored); GHG_{ΔL} becomes solely dependent on the loss of CO₂ capture opportunity. In this case, EROI_g reduces to 1.79 for the wind farm and 0.64 for the PV plant. Thus, without the capacity to remove CO₂ by photosynthesis from the vast amounts of land set aside to offset biodiversity losses, the EROI_g performance of both plants is significantly reduced. For the PV plant, as $EROI_g < 1.0$, the plant is unable to produce net energy after investing energy in environmental maintenance. These results however depend on the assumptions made on the type of land the plant is located on and its corresponding biodiversity offset. This is examined in case 2 below.

Case 2. Existing site: land with no vegetation option, offset prospects not required

The plant is built on land that neither has existing vegetation (eg. desert or ocean) nor does it have the potential to be vegetated, and hence does not have any loss of carbon capture opportunity and does not require any biodiversity offset. The resultant EROI_g in this case would be 12.76 for wind and 2.92 for solar. The benefits of mounting RE systems on lands with low vegetation and biodiversity is clear-it provides reasonably high EROI_g values while having minimal land requirements.

If the land used to locate an energy generation plant was degraded due to previous use (eg. agricultural land), the proposed plant would also require a share of biodiversity offset. This is because that degraded land would have had a potential for rehabilitation and re-establishment of biodiversity if the plant was located elsewhere. However, damaged lands will be classified under “low significance” (refer to Table 3) and could potentially have more soil sealing. Therefore, one advantage of using degraded land over native forests in that instance could be in the lower area of land required for biodiversity offsets.

5. Discussion

The results show that the inclusion of ESME for the cases examined

Table 5

Lifecycle assessment results for 1.0kWh of electricity.

LCA impacts		Wind 50 MW		Solar PV 100 MW	
Impact category	I_i (units)	Impact I_i	ESME i/E_{gross} (kWh/kWh)	Impact I_i	ESME i/E_{gross} (kWh/kWh)
Global warming indirect emissions $I_{\text{GHG}-i}$ (embodied impact)	kg CO ₂ eq/kWh	8.27×10^{-3}	2.02×10^{-2}	2.62×10^{-2}	6.41×10^{-2}
Global warming direct GHG emissions $I_{\text{GHG}-d}$	kg CO ₂ eq/kWh	3.77×10^{-3}	1.85×10^{-3}	1.48×10^{-2}	7.25×10^{-3}
Stratospheric ozone depletion	kg CFC11 eq/kWh	3.37×10^{-9}	3.92×10^{-6}	1.43×10^{-8}	1.67×10^{-5}
Ionizing radiation	kBq Co-60 eq/kWh	5.41×10^{-4}	1.93×10^{-4}	4.32×10^{-3}	1.54×10^{-3}
Ozone formation, Human health	kg NO _x eq/kWh	3.14×10^{-5}	2.51×10^{-4}	1.03×10^{-4}	8.24×10^{-4}
Fine particulate matter formation	kg PM _{2.5} eq/kWh	1.15×10^{-5}	3.84×10^{-4}	3.17×10^{-5}	1.06×10^{-3}
Ozone formation, Terrestrial ecosystems	kg NO _x eq/kWh	3.28×10^{-5}	2.62×10^{-4}	1.08×10^{-4}	8.66×10^{-4}
Terrestrial acidification	kg SO ₂ eq/kWh	4.61×10^{-5}	5.13×10^{-6}	1.81×10^{-4}	2.01×10^{-5}
Freshwater eutrophication	kg P eq/kWh	7.82×10^{-6}	2.60×10^{-5}	2.76×10^{-5}	9.20×10^{-5}
Marine eutrophication	kg N eq/kWh	6.41×10^{-7}	6.41×10^{-8}	2.97×10^{-6}	2.97×10^{-7}
Terrestrial ecotoxicity	kg 1,4-DCB/kWh	4.95×10^{-2}	1.10×10^{-2}	4.34×10^{-1}	9.65×10^{-2}
Freshwater ecotoxicity	kg 1,4-DCB/kWh	4.01×10^{-3}	8.91×10^{-4}	5.49×10^{-3}	1.22×10^{-3}
Marine ecotoxicity	kg 1,4-DCB/kWh	1.03×10^{-3}	2.29×10^{-4}	1.69×10^{-3}	3.75×10^{-4}
Human carcinogenic toxicity	kg 1,4-DCB/kWh	7.91×10^{-6}	1.76×10^{-6}	1.77×10^{-5}	3.92×10^{-6}
Human non-carcinogenic toxicity	kg 1,4-DCB/kWh	4.60×10^{-4}	1.02×10^{-4}	1.79×10^{-3}	3.98×10^{-4}
Lifecycle land L_R	m ² a crop eq/kWh	6.62×10^{-4}	1.06×10^{-4}	2.56×10^{-5}	4.12×10^{-6}
Biodiversity Offset - based on land L_B	m ² /kWh	5.28×10^{-4}	1.47×10^{-5}	1.34×10^{-3}	3.72×10^{-5}
Loss of CO ₂ capture opportunity $I_{\text{GHG}-DL}$	kg CO ₂ eq/kWh	1.94×10^{-1}	4.73×10^{-1}	4.91×10^{-1}	1.2
CO ₂ capture by offset land $I_{\text{GHG}-B}$	kg CO ₂ eq/kWh	5.81×10^{-1}	-4.93×10^{-1}	2.21	-1.26
Mineral resource scarcity	kg Cu eq/kWh	2.23×10^{-4}	–	4.33×10^{-4}	–
Fossil resource scarcity	kg oil eq/kWh	2.84×10^{-3}	–	9.40×10^{-3}	–
Water consumption	m ³ /kWh	1.15×10^{-4}	6.93×10^{-4}	8.80×10^{-4}	5.28×10^{-3}
$ESME/E_{\text{gross}}$	kWh/kWh	1.60×10^{-2}		1.15×10^{-1}	
E_i/E_{gross}	kWh/kWh	4.22×10^{-2}		1.63×10^{-1}	
% $E_{\text{net}}/E_{\text{gross}}$	% net	96		84	
% $E_{\text{netg}}/E_{\text{gross}}$	% net	94		72	
EROI _g (with CO ₂ offset)		17.19		3.59	
EROI _g (without CO ₂ offset)		1.81		0.65	
EROI		23.70		6.13	

reduces EROI_g to be at least 1.5 times lower than EROI. As the proposed wind and PV systems in this work are hypothetical, the analysis assumes that the plant operates in a grid providing continuous demand of which 10% of the energy is curtailed. This study also assumes that the emissions are directly captured from effluent and will not remain in the environment for >20 years. Actual plants may differ in operation, components, supply chain, and so on, and some of these differences are explored below for the cases presented in Table 5.

5.1. Impact of battery back-up

In future grids where growing integration of intermittent RE systems is expected (Bird et al., 2016), energy storage is needed (Brouwer et al., 2014). This is driven by concerns over RE generation including: meeting continued demand flow (Bird et al., 2016); managing daily and seasonal intermittency; maintaining grid safety in extreme weather (Pudjianto et al., 2013); shifting peaks (Pilpol et al., 2019); avoiding curtailment (Denholm and Mai, 2019), and so on. This design options analysis assesses the impact of battery storage on the EROI_g of the solar PV and wind energy systems assessed in this work.

Different energy generation technologies and corresponding operating conditions have different storage requirements (Bird et al., 2016). The purpose of this section is not to provide a direct comparison between the two systems for impact of battery storage. In this study, data on suitable wind and solar storage size is obtained from literature studies that consider curtailment and RE future demand. Denholm and Mai (2019) analysed the impact of 55% solar and wind infiltration into the grid on curtailment. Their results show that curtailment would reduce by approximately 40% by adding approximately 4–8h of battery storage with approximately 7% plant capacity.

This design options analysis adopts an 8h battery storage in both the wind and solar PV cases. Batteries are assumed to match the plant capacity, therefore 460 MWh battery storage for the wind farm and 920 MWh for the solar farm if a 15% minimum state of charge is assumed for each case. An approximate 10% increase in the number of panels/

turbines is assumed to be provided to cater for charging the batteries while keeping the plant in operation after discharge. Assuming an average battery life of 20 years (Cucchiella et al., 2015), the battery storage system will thus require replacement at least once during the PV system's 30-year lifecycle. For the wind farm, the battery storage system remains unchanged during the wind farm's life (20 years). E_{gross} is assumed to increase in both systems by approximately 5% due to reduction in curtailment.

The design options analysis results (Table 6) show a decrease in EROI for both solar PV and wind energy systems with the inclusion of battery back-up, due to the embodied energy in battery manufacturing. The EROI_g is up to 2.5 times lower than the reference case when batteries are added. Thus, the use of batteries to reduce intermittency comes at considerable cost to green energy production.

5.2. Impact of a renewable powered manufacture

As many of the environmental impacts occur in the plant's supply chain, shifting supply chain energy use away from fossil fuels to RE in the manufacturing of major plant components is examined. RE is assumed to be used to erect the panels and turbines, and for the manufacturing of the panels and turbines after obtaining the pre-manufactured components.

Renewable manufacturing use improved the EROI_g by up to 20% (when compared to the reference case) in both cases, making the EROI_g values of plants with renewable manufacture the highest among all

Table 6Results of the design options analysis showing the on EROI and EROI_g.

	PV		Wind	
	EROI	EROI _g	EROI	EROI _g
No storage – reference	6.13	3.59	23.70	17.19
Battery included	3.93	2.00	11.89	6.20
Renewable manufacturing	6.28	3.66	26.41	19.13
Midpoint H diluted	6.13	0.46	23.70	3.02

those shown in Table 6. Also, as shown in Table 6, an increase in EROI is noticed for both systems when the supply chain energy is changed to RE. This small increase occurs as a consequence of the way fossil fuel heating values are accounted for in LCA and should be ignored (Arvesen and Hertwich, 2015).

5.3. Impact of delayed ecosystem maintenance

As the implementation of environmental maintenance may not be enforced as quickly as anticipated, plant emissions may reside in the environment for >20-years, and clean-up may not be possible at the source. If this was the case, emissions would become diluted in the environment requiring further energy for clean-up. This delayed implementation of environmental maintenance changes the LCA method's time horizon for long-lived pollutants. The Individualist (I) cultural perspective in this case (used as the scenario driving a 20-year time perspective in this study) changes to a Hierarchist (H) cultural perspective with a business-as-usual scenario (with 100-year time horizon) or an egalitarian perspective with a consensus model (with 1000-year-infinite time horizon). Those alternative scenarios assume in the LCA computation that proper management or future technology development is delayed and cannot fully avoid future damages.

In addition to the cultural perspective, energy consumption values attributed to every ISR technique would increase due to the need for treating diluted contaminants in the environment (e.g., in the oceans, rivers and atmosphere) rather than concentrated contaminants in effluent or stacks. An example of that is the use of Direct Air Capture (DAC) to capture CO₂ from the air or diluted sources rather than capture of CO₂ from the stack of a power plant or manufacturing plant where CO₂ concentrations are elevated. DAC process consumes approximately 5 times more energy (Keith et al., 2018) than stack capture to remove a kilogram of carbon dioxide (Raganati et al., 2014).

The worst EROIg results obtained in this assessment were associated with the midpoint diluted case where pollutants reside in the environment for >20 years. Table 6 shows that the EROIg are up to 6.5 times lower than the reference (from an EROIg of 3.59 to 0.46) when delayed action is taken. The impact of delayed ecosystem maintenance highlights the importance of fast action on ecosystem maintenance. When ecosystem maintenance is delayed, the EROIg is reduced greatly (up to

85%) in both cases. This leads to an EROIg < 1 for the case of solar PV. Thus, when ecosystem maintenance is delayed, the solar PV system is unable to produce net green energy.

5.4. Discussion - net green energy production

As shown in Fig. 2, inclusion of ESME means that the size of an energy plant must be increased to meet a fixed energy demand, but this exacerbates the environmental impact which further increases the ESME required.

Table 7 shows the % increase in total system size if oversizing was applied to deliver 1 MJ of E_{netg} demand for all the design options assessed in this study, based on a possible technology mix of 70% wind/30% solar. As shown, a minimum of 44% increase in size is needed to deliver the same amount of net energy to society if this energy was to be green.

5.5. Discussion - summary

The critical importance of land offsets to protect biodiversity was acknowledged at the 15th United Nation's Convention on Biological Diversity (COP-15) which adopted the post 2020 global biodiversity framework (UN COP15, 2022). The convention included among its major goals the need to safeguard biodiversity, particularly in critically endangered ecosystems. Significant land area will be required to achieve this, despite the increasing demand for agriculture and food production (Banks-Leite et al., 2020), housing, transport, and energy generation. This highlights the importance of land rehabilitation especially for damaged land. As demonstrated in this work, given the significant size of land required to meet the projected energy requirements, if the Earth's biodiversity was to be safeguarded, the need to limit environmental impact including biodiversity loss while achieving high energy return must become part of future energy planning (Barnard et al., 2021).

6. Conclusions

All forms of energy generation are linked to the ecosystem, use its resources, and have impacts on it. Commensurate with the increase in

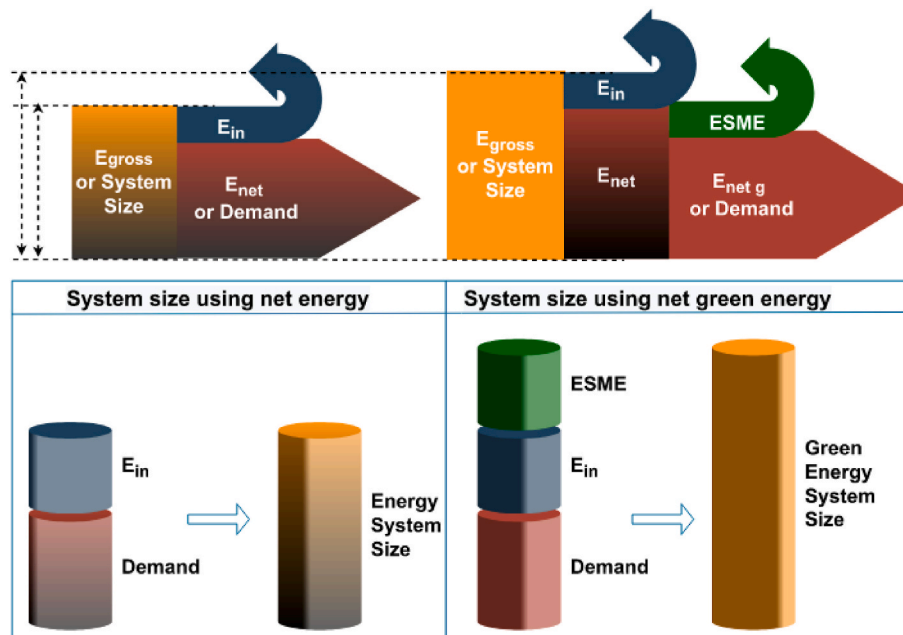


Fig. 2. System sizing for net green energy provision. Diagram construction software (Graph, 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 7

System implications of the design options analysis at 70% Wind 30% PV.

	System: 70% wind and 30% PV		Green system: 70% wind and 30% PV		Green system size increase
	EROI-sys	System level E_{net}/E_{gross} (kWh/kWh produced)	EROI-g-sys	System level E_{netg}/E_{gross} (kWh/kWh produced)	% Energy system size increase for a constant E_{gross}
No storage	12.74	11.74	8.04	7.04	40%
Battery included	7.40	6.40	3.80	2.80	56%
Renewable manufacturing	13.46	12.46	8.44	7.44	40%
Midpoint H diluted	12.74	11.74	1.13	0.13	99%

global energy demand over the years, these impacts have increased greatly and can no longer be ignored. If energy generation systems are to produce “green energy”, these systems need to invest a portion of their produced energy in cleaning-up their own emissions. Energy cost associated with this clean-up is called ecosystem maintenance energy (ESME). Including ESME costs in energy accounting reduces the net energy available to society from a generation plant. This paper quantifies the potential of two energy generation systems to produce net green energy E_{netg} and green energy return on energy invested (EROIg) to society. Quantifying EROIg allows for the selection of energy generation plants on the basis of both environmental impact and energetic potential using a single metric.

This work expands on the EROIg computation methodology developed by Daaboul et al. (2022) by assessing land related biodiversity impacts, loss of carbon capture opportunity, delayed maintenance of the ecosystem and carbon capture prospect in biodiversity offset land and a wider range of environmental impacts derived from LCA. An onshore 50 MW wind farm and 100 MW solar PV farm producing an equivalent amount of annual energy were used as case studies to test this expanded method. These systems were chosen because of their likely dominance in future energy production. After including ESME for each of the systems in EROIg and E_{netg} computation, it was found that both wind and solar plants were capable of producing net green energy over their lifetime with wind generation having greater green energy potential. After accounting for ESME, the EROIg for wind and solar produced electricity was approximately 35% and 40% lower than their corresponding EROI respectively.

A number of options were assessed to examine the impact of adding battery storage; using RE to power manufacturing in the supply chain; and assuming delayed removal of diluted impacts from the environment. The analysis showed a decrease in EROI and EROIg for both solar PV and wind energy systems in the case of battery back-up. The best EROIg in both systems was recorded in the renewable manufacturing case and the worst EROIg in the delayed removal case. One major finding is the large impact of plant location and biodiversity offset prospects on EROIg. Plants located on vegetated land without biodiversity offsets are associated with low EROIg, $EROIg < 1$ for PV. This is because the removal of vegetation from the vegetated land incurs loss of carbon capture prospects, and the absence of biodiversity offsets removes the option of a carbon sink offsetting the associated GHG emissions. This makes siting RE plants on land with no vegetation options or the more efficient use of land for multiple purposes a more viable option if the generation was to be green.

Including different forms of ecosystem maintenance in energy planning will become increasingly important, given the scale of production required to meet projected global energy needs. Failure to implement ecosystem maintenance measures and pay ESME costs will result in a continual decline of ecosystem services. To avoid this, utility-scale energy system selection and development must be based on an approach that combines maximising net energy production whilst removing environmental impacts. This work has highlighted the large energy cost associated with removing environmental impacts for two critical RE technologies: solar PV and on-shore wind energy. While both were found to deliver net (green) energy after accounting for inputs and

ESME costs, outcomes have been shown to be sensitive to a range of factors, including offsets required, how and when impacts are removed, and energy storage needs. Further sensitivity can be expected to result from RE resource quality. Consequently, meeting future energy demand with green energy will require detailed individual analysis of proposed energy plants. This study also demonstrated the importance of carbon capture by photosynthesis and biodiversity offsets along with their effect on improving EROIg. Given the promise of crop-based biomass energy generation to capture the majority of its carbon by biomass photosynthesis, it is essential that the prospects of green energy generation by other methods such as biomass be examined.

CRediT authorship contribution statement

Jessica Daaboul: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing. **Patrick Moriarty:** Conceptualization, Writing – review & editing. **Damon Honnery:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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