Sustainable energy planning for remote islands and the waste legacy from renewable energy infrastructure deployment

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Abstract

The transition towards a sustainable energy mix is required to achieve Sustainable Development Goal 7 for affordable and clean energy. Remote islands not connected to grid which depend on diesel generators may appear ideal because they can benefit from a variety of renewable energy sources. However, renewable energy deployment requires a lifetime perspective to not inherit waste and other problems to future generations. The aim of this paper is to present a life cycle sustainability framework developed and applied for the case of the island of Ushant off North West France. Seven renewable energy generation scenarios were examined and assessed using technoeconomic, social and environmental indicators utilising life cycle costing and life cycle assessment modelling. The results show that only three out of the seven examined renewable energy scenarios manage to cover the 6,807 MWh per annum demand. These scenarios can improve all the indicators against the business-as-usual diesel generation scenario except the ones related to toxicity and reduce greenhouse gas emissions by more than 92%. The easy-to-use framework allows the users to adjust their scenarios and receive useful insight about the nature of the trade-offs between the various indicators. It can also be adapted and updated to include more technologies and support the investigation of more sustainable energy scenarios of other remote island cases in the future.

Keywords: life cycle assessment, sustainable energy, circular economy, remote islands, waste, renewable energy

1 Introduction

Climate change continues to be one of the most pressing issues and it has escalated to the degree that policy makers use the terms ‘climate emergency’ and ‘climate crisis’. There have been considerable efforts to tackle this issue and some of them have been concentrated on the energy sector, one of the main contributors to climate change. There has been a great emphasis on shifting away from fossil fuels and towards renewable energy technologies in order to make the energy mix as low carbon as possible.

The transition to renewables is even more important in areas that are not connected to the electricity and/or gas grid because these areas cannot benefit from the penetration of potentially lower carbon fossil fuel technologies such as natural gas with carbon capture and storage and/or the inclusion of nuclear energy in the energy mix. A connection to the grid can be a more complicated task technically, administratively and financially compared to the installation of photovoltaics and wind turbines for remote/isolated areas like islands. Moreover, as islands are geographically isolated by nature and therefore closed energy systems, it can be easier to assess their potential resources for renewable energy generation in relation to energy demand. In addition, as opposed to mountainous remote areas, islands can benefit from marine and offshore renewables such as wave, tidal and offshore wind and together with the photovoltaics and the onshore wind turbines they can have a wider range of options to choose from. This is important because carbon footprint is not the only matter of concern and choosing the lowest carbon renewable energy technology may not necessarily be the best option.

Technoeconomic criteria were usually the most important because the development of new energy infrastructure is a significant investment and a matter of security. A resource assessment is necessary to identify the suitable energy generation technologies that can be adopted and their expected performance. In addition, the anticipated costs should be calculated not only for the capital expenditure but also for the operational phase through a lifetime perspective. This can be achieved with a life cycle costing (LCC) which can cover the economic assessment. The links between economic and environmental sustainability have been explored, with a focus on whether alternative energy technologies such as wind and solar power meet the minimum energy return on investment requirements (Hall and Klitgaard, 2012) as well as on the interactions between the economics of natural resources and environmental protection (Zweifel et al., 2017).

The problem of burden shifting either to other areas or future generations and the potential trade-offs between various environmental impacts can be dealt with using the standardised methodology of life cycle assessment (LCA) (ISO, 2006). LCA can be used as a tool that takes into account the whole life cycle of a product or service and can assess a wide range of environmental impacts such as climate change, ozone depletion and toxicity. The recent uproar on the plastic waste and the challenge the local authorities face to deal with the amount of waste produced has fuelled new concerns and highlighted the problem of burden shifting when it comes to solving environmental issues.

Moreover, for any energy system to be sustainable, the social pillar should also be covered and in the case of an island, the impacts on the local communities could be equally important. Although renewables should be welcomed because of their reduced carbon emissions, this is not a direct and tangible benefit for the inhabitants. On the other hand, concerns over associated wastes at the end of life of the additional infrastructure might spark oppositions. Other issues might also come up especially for the wind turbines such as flickering, noise etc but this technology is mature enough and following the regulations can alleviate such issues.

It is evident that the problem of configuring a sustainable energy mix has many aspects and decision should be made based on many criteria, following a life cycle perspective while covering all the aspects of sustainability. The development of a life cycle sustainability assessment methodology is not new and several approaches have been proposed, bringing up the methodological challenges (Costa et al., 2019). The decarbonisation of national electricity mix have been extensively studied using the conventional LCA framework. Some studies focus on understanding the environmental impacts of current and past electricity mix in various countries such as Mexico (Santoyo-Castelazo et al., 2011), Portugal (Garcia et al., 2014) and Belgium (Messagie et al., 2014) but lack the investigation of future scenarios. Some studies evaluate the environmental impacts of future electricity systems in Denmark (Turconi et al., 2014) and Czech Republic and Poland (Burchart-Korol et al., 2018) but focus mainly on carbon emissions. This narrow focus could mean environmental burdens being shifted to other impact categories, as demonstrated in a study on future electricity mix in the UK (Kouloumpis et al., 2015). Therefore, broadened LCA frameworks that include wider aspects of sustainability such as costs, social acceptance and technical stability have emerged in more recent studies on electricity systems in countries such as Turkey (Atilgan and Azapagic, 2016), Chile (Gaete-Morales et al., 2018), UK (Kouloumpis and Azapagic, 2018) and Greece (Roinioti and Koroneos, 2019).

However, all the above-mentioned studies evaluate relatively large national energy systems with availability of diverse technologies, significant renewable energy resources and/or the potential to connect with energy systems in other countries. The approaches adopted to assess the decarbonisation scenarios of these large systems were usually based on assumptions on different generation mixes to meet demand. However, these approaches might not work for small islands such as Mauritius (Brizmohun et al., 2015) and the Azores island of Graciosa (Stenzel et al., 2017) as it is often difficult to achieve complete decarbonisation for these isolated systems without jeopardising energy security mainly because of constraints in renewable energy resources and/or network infrastructure Fiji (Michalena et al., 2018). The involvement of stakeholders is also more important for the islands as the impacts of energy system transition can be more “visible” and affect the acceptance of certain technologies. Therefore, an LCA based sustainability framework that can assess potential environmental, economic and social impacts of island energy systems with engagement of stakeholders is necessary. In addition, an accessible tool that stakeholders can use to evaluate different energy scenarios and understand the impacts would be highly beneficial. This is because although there are established and widely used LCA tools such as SimaPro (PRé Sustainability B.V, 2021), GaBi (Sphera Solutions GmbH, 2021) and OpenLCA (GreenDelta GmbH, 2021), they typically incur noticeable costs on software licences or databases and require expert knowledge to use.

A Life Cycle Sustainability Framework (LCSF) with an accessible tool was developed in this study to fill this gap and enable stakeholders to investigate the environmental, economic and social aspects of future energy scenarios for islands and make more informed decisions on their low carbon transitions. The aim of this paper is to present the LCSF developed and demonstrate its application using the island of Ushant off North West France as a case study.

2 Materials and method

This section provides describes the LCSF and the model developed and provides information for the case study used so that their implementation on this case can be illustrated.

2.1 Life Cycle Sustainability Framework

The LCSF developed is based on the standardised LCA and it also includes the other two pillars of sustainability: economy and society and was developed within the framework of ICE project (Yan and Kouloumpis, 2020). For the electricity generation technologies that can be used on an island, LCA models were developed and the results can be used for the design of a multi-criteria decision analysis method to support the holistic assessment and ranking of different future energy system options. The LCSF is illustrated in Figure 1 and the description follows in the next paragraphs.

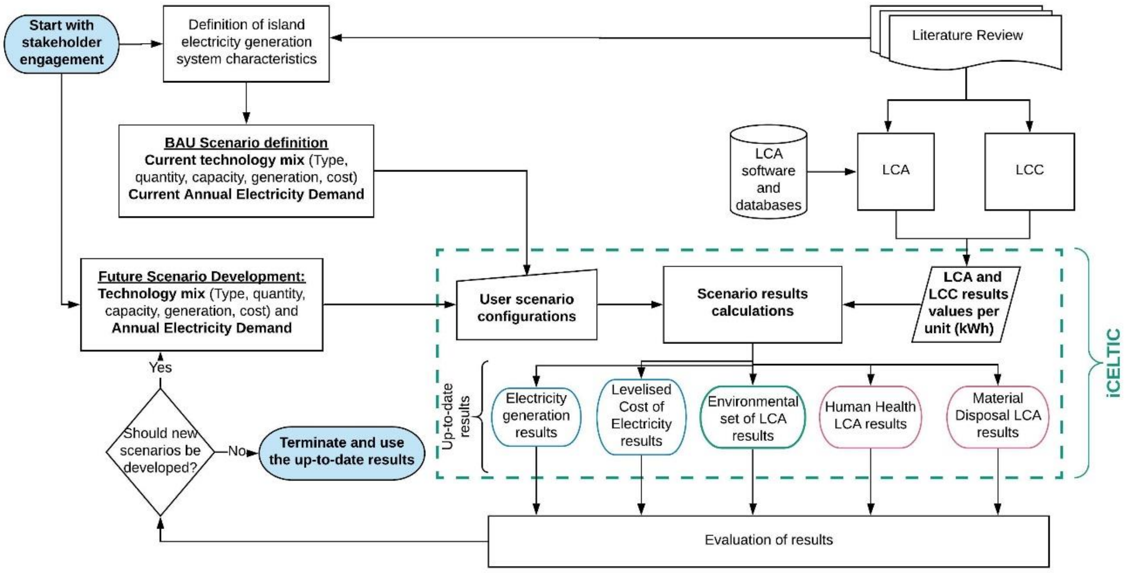

Figure 1 Life Cycle Sustainability Framework Flowchart

The first step is to engage the relevant stakeholders which can be the local communities, the national grid moderators and energy providers and the local and national authorities. Members of the scientific community as well as companies that develop renewable energy technologies could contribute quite significantly to new sustainable energy plans because they are aware of their technology readiness levels. The way these stakeholders can be engaged varies and the level of their engagement depends on those who lead the to choose the most appropriate way, be it private meetings, open days, workshops, surveys and other forms of participation and consultation methods. The stakeholder engagement can provide two main outputs that are necessary when following the LCSF. The first is to define the current island electricity generation characteristics and this can be supported by the relevant literature such as technical reports, policy documents and scientific publications). The second is to contribute to the development of the future energy scenarios. In both cases, what needs to be defined both for the current situation and the future scenarios are: i) the annual electricity demand (for example 10,000 kWh) and ii) the technology mix of the electricity generation technologies, namely the number, type, nominal capacity, capacity factor (c.f.) and cost per MWh (for example 2 onshore wind turbines of 800 kW capacity, 30% c.f. and 100 £/MWh). The capacity factor (c.f.) is the ratio of the actual electricity output over a given period of time to the maximum possible electricity output (assuming its continuous operation at full nameplate capacity) over that period.

Once the scenarios are defined, and the components that constitute the current and future electricity generation mix are known, a series of LCAs should be performed for each one of them. LCA comprises four phases: i) the goal and scope definition, ii) the inventory analysis, iii) the impact assessment and iv) the interpretation which runs throughout the LCA. During the inventory analysis a Life Cycle Inventory (LCI) is compiled based on data collected for the resources (materials and energy) inputs and wastes/emission outputs for each activity. This LCI is used to proceed with the impact assessment phase where the emissions/wastes and resources are translated into a limited number of environmental impact scores. The stakeholders can affect the decision of the life cycle impact categories that need to be examined. A model is built using an LCA software like GaBi v8.7 (Thinkstep A.G., 2019) and the commercial LCI database like ecoinvent v3.5 (Wernet et al., 2016) that was used in this case and which allows for the calculation of the results for many potential environmental impacts. In these LCA models the functional unit used was the 'the generation of 1 kWh of electricity from one piece of energy mix component (e.g. wind turbine) considering an expected lifetime of 20 years'. These assessments are cradle-to-gate and they exclude the EoL treatment although they do include a set of indicators for the materials that are expected to be disposed of. The main reason is that these refer mainly to future scenarios and it is difficult to predict whether the infrastructure will be granted extension, upgraded, or dismantled and whether the disposed materials will be landfilled, incinerated or recycled. The boundaries of these studies exclude the local transmission and distribution (T&D) grid which can remain the same as the already existing one. Nevertheless, as they are closed systems, a storage option with Li-ion battery is included and can be updated when more LCA models of storage technologies become available in the future. Finally, the models are focused on the demand for the electricity that needs to be generated excluding losses during T&D. The LCI data referring to the system within the boundaries have been collected from the relevant literature and databases like ecoinvent (Wernet et al., 2016) and have been processed using GaBi software version 8.7 (Thinkstep A.G., 2019). Using the CML impact assessment method, the potential impacts were calculated for each technology for the functional unit.

Similarly, a LCC -or Life Cycle Cost Analysis (LCCA) as it is also known- can be used to evaluate the potential economic performance which ideally takes into account the Development and consenting (D&C), Production and acquisition (P&A), Installation and commissioning (I&C), Operation and maintenance (O&M), Decommission (DECOM) (Myhr et al., 2014). The LCC results in our framework are given using a metric based on the expected energy production during the life span and the Levelised Cost of Energy (LCOE). In the LCSF, along with the LCoE the amount of the demand that is covered by the chosen renewable electricity generation portfolio is also used as an indicator of energy security. This additional indicator can show whether the investment in a proposed renewable energy plan is delivering the expected outcome and it can be useful to rule out scenarios that might seem economical at first but turn out to fail risking all the capital expenditures realised.

All this information is embedded in the Intelligent Community Electricity Lifecycle Technology Impact Calculator (iCELTIC) which is developed in Excel and which can be available to the stakeholders. The main purpose of iCELTIC is to provide a user interface so that the results from the LCA and LCC and be utilised and combined with the current and future scenario configurations. The users can see two sheets, one for inputs where they can input the values for the current and future preferred scenarios and one for the outputs which provides the results for each one of the scenarios in both tabular and graphic representation.

The users can then evaluate the results they receive and share them with the rest of the stakeholders. If these are deemed to be satisfactory, then the process can be terminated, and the users can use the tables and graphs for further analysis. The cells in the outputs are locked so that the users do not accidentally delete or overwrite the results. In the case that the results are not satisfactory, and the users would like to introduce new scenarios or change some of the values of the existing ones, they can do so in the Inputs sheet and repeat the process. The flexibility and ease of use of iCELTIC supports this iterative and interactive process so that the stakeholders can engage in a productive and efficient way. This helps the investigation of many scenarios and performance of sensitivity analyses to examine whether the results of the proposed scenarios are robust. This is also especially useful when they would like to identify trade-offs between improving their sustainability indicators, for example to investigate whether the minimisation of the cost could increase the carbon footprint. The next subsection provides information for the case of Ushant island and the following subsections describe in detail the LCA and LCC.

2.2 The case study of Ushant island

The first case study to implement the LCSF methodology in the ICE project is Ushant, an island off the North West coast of France. The island that has tourism as its main industry can see its population expanding from the approximately 850 residents by hosting over 100,000 visitors who travel to the island annually especially in the summer (Bretagne Développement Innovation, 2018). The main source of power are mainly the four diesel generators supplying up to 4.1MW. It is estimated that the generators may consume more than 2,000,000 litres of fuel per year (Natacha Haas Guégo, 2018) and this is used as a Business as Usual (BAU) scenario. During 2015 a Sabella D10 1.1MW tidal turbine supplied power to the island (Paboeuf et al., 2016). In 2017 solar arrays were installed with a view to expand further the solar generation (SDEF, 2018). With the aim to achieve 70% of electrical generation from renewable technologies by 2020 and 100% renewable generation by 2030 there is clearly a need to investigate the use of more renewable technologies on or around the island such as solar, wind and further tidal technologies. During the early stages members of the project consortium visited Ushant and met with local stakeholders such as local authorities and inhabitants. Based on the feedback of these meetings seven scenarios were developed as described in the ICE project reports for the overview of the renewable energy policy and regulatory considerations in Ushant (Fitch-Roy and Connor, 2018), for the overview of renewable energy supply potential (Hardwick et al., 2018a) and for the analysis of smart grid and storage options in a demand side assessment context (Mahmood et al., 2019). These scenarios were created to assess the extent to which a combination of solar, wind and tidal generation technologies can meet the island's electrical demand. Some of these scenarios may not be possible as potential technical, environmental or socio-political constraints were not considered during their design. Table 1 shows the data input to the iCELTIC tool for the Ushant case study.

Table 1 Case study inputs to model

Plant/ installation name	**Capacity of electricity plants/installations in kW (Capacity factors of technologies)**						
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
Wind farm small	300 (57.5%)						
Wind farm medium		800 (62.3%)					800 (62.2%)
Wind farm large			2000 (61.6%)				
Tidal turbine				1000 (11.4%)	1000 (11.4%)	2000 (11.4%)	1000 (11.4%)
PV Sports Hall	45 (14.7%)			45 (14.7%)		45 (14.7%)	
PV Salle Polyvante	13.2 (12.4%)			13.2 (12.4%)		13.2 (12.4%)	
PV Auberge	8.8 (11.0%)			8.8 (11.0%)		8.8 (11.0%)	
PV Mairie	9 (12.3%)			9 (12.3%)		9 (12.3%)	
PV Service Technique	113 (9.5%)			113 (9.5%)		113 (9.5%)	
PV 20% suitable rooftops		3600 (12.3%)	3600 (12.3%)		3600 (12.3%)		3600 (12.3%)

S1-Planned solar (5 sites) and 300kW wind turbine; S2-Extensive solar (20% of rooftops), and 800kW wind turbine; S3-Extensive solar and 2MW wind turbine; S4- 1MW tidal turbine and planned solar; S5-1MW tidal turbine and extensive solar; S6-Two 1MW tidal turbines and planned solar; S7-1MW tidal turbine and extensive solar and one 800kW wind turbine

2.3 Life Cycle Assessment

LCA models were developed using the materials and assumptions as described in the paragraphs that follow. The common basic assumption is that the lifetime is 20 years and that the network remains the same so there is no need to model the additional components for the transmission and distributions such as power lines, pylons, and substations. To keep consistent with the capacity factors allocated by the initial models for the components used from the ecoinvent database, these remain the same when calculating the impacts per kWh generated which is the functional unit. The iCELTIC has embedded a function that adjusts the overall impacts by dividing the capacity factor used in the LCA model with the capacity factor that the user defines based on the actual electricity generated. The capacity factors used as inputs for the Ushant scenarios have been calculated from the given capacities and generation estimated in the scenarios described in the ICE T1.4 report (Hardwick et al., 2018b). Table 2 presents the specifications related to energy generation technology.

Table 2 Energy generation technology specifications

Energy generation plant/installation	Energy generation technology	Reference
Wind farm small	Based on Nordex N50/800 and scaled down to match E33-300 assuming 20% capacity factor	Ecoinvent 3.5 ‘Electricity production, wind, <1MW turbine, onshore’ modified to consider tower weight c36.7 tonnes and moving parts (nacelle, blades, rotor) weight c18.7 tonnes
Wind farm medium	Based on a Nordex N50/800 and a capacity factor of 20.29%	Ecoinvent 3.5 ‘Electricity production, wind, <1MW turbine, onshore’ of the ecoinvent 3.5
Wind farm large	Based on a 2MW Vestas onshore wind turbine with 24.25% capacity factor	Ecoinvent 3.5 ‘Electricity production, wind, 1-3 MW turbine, onshore’
Tidal turbine	Based on literature an 1MW tidal generator LCA model was created assuming a 10% capacity factor	See table in Appendix and (Howell et al., 2013)
PV Sports Hall **PV Salle Polyvante** **PV Auberge** **PV Mairie** **PV Service Technique** **PV 20% suitable rooftops**	Based on a 3kWp multi-Si photovoltaic slanted roof installation with 17.31% capacity factor	Ecoinvent 3.5 ‘electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si’

For the electricity generated by the 2MW wind the ‘Electricity production, wind, 1-3 MW turbine, onshore’ from the ecoinvent 3.5 database was used because it is also based on a 2MW Vestas onshore wind turbine. That model assumes a 24.25% capacity factor and includes both the turbine construction and the network connection. The model for the 800kW wind turbine is based on the ‘Electricity production, wind, <1MW turbine, onshore’ of the ecoinvent 3.5 dataset which is based on a Nordex N50/800 (Bauer and Matysik, n.d.) and a capacity factor of 20.29%. This type of turbine has the same nominal capacity, similar diameter (50m and 52.9m respectively) and can have the same 50m hub and therefore tower as the Enercon E53-800 (ENERCON GmbH, 2016) used in the scenarios developed for Ushant (Hardwick et al., 2018b). Therefore, using the same fixed parts (i.e. foundations, tower, etc) and the same moving parts (i.e. nacelle, blades etc) creates a relatively representative model. Unfortunately, an existing dataset for a 300kW close to the Enercon E33-300 (Bauer and Matysik, n.d.) used in Ushant scenarios is not available in this database version and more work was required. The tower height remains the same but the weight considered to be 36.7 tonnes differs a lot from the much heavier tower mass of the Nordex N50/800 (Bauer and Matysik, n.d.) model so adjustments had to be made and the masses for the steel and energy re-estimated. The moving parts are even more different and the total weight of the moving parts (nacelle, blades, rotor) of the E33 (approx. 18.7 tonnes) can be approximately half of the N50 (approx. 39 tonnes). Using the N50 as a basis and scaling down accordingly, a relatively adequate LCA model was created.

For the photovoltaics installed on buildings, a set of ecoinvent 3.5 datasets have been used: ‘electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si’, ‘electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si’ and ‘electricity production, photovoltaic, 3kWp facade installation, multi-Si’. The photovoltaics are a more homogenous and scalable technology so the 3kWp LCI datasets can be linearly upscaled to 9kWp and get reliable LCA results. The capacity factors considered for the flat-roof and slanted-roof were 17.31% while for the façade 11.6%. The photovoltaics in our scenarios are slanted roof type. Although not explicitly described in the seven scenarios, an open ground photovoltaic and Li-ion storage were added to the model to facilitate future analyses. For the open ground photovoltaics the ecoinvent 3.5 dataset ‘electricity production, photovoltaic, 570kWp open ground installation, multi-Si‘ was used and for the storage the ecoinvent 3.5 dataset ‘battery production, Li-ion, rechargeable, prismatic‘ was used.

For tidal, data were not available in our LCA databases. Therefore, an 1MW tidal generator LCA model was created using data from the literature (Howell et al., 2013) and assuming a 10% capacity factor. More details on the type and quantity of materials used can be found in Table A1 in the appendices.

Based on the above LCA work the per kWh results were calculated and they are provided in Table A2 in the appendices. These results are based on the specific conditions and data available at that time and may and could change in the future depending on the circumstances and requirements. In this case a set of indicators were chosen based on the CML2001 - Jan.

2016 (Guinée, 2002) life cycle impact assessment method: i) Abiotic Depletion Potential (Elements), ii) Abiotic Depletion Potential (Fossils), iii) Acidification Potential, iv) Eutrophication Potential, v) Freshwater Aquatic Ecotoxicity Potential, vi) Global Warming Potential, vii) Marine Aquatic Ecotoxicity Potential, viii) Ozone Layer Depletion Potential, ix) Photochemical Ozone Creation Potential, x) Terrestric Ecotoxicity Potential. The CML method also gives results for Human Toxicity Potential (HTP), which was used as an indicator for human health. The LCI provides data for the materials that are expected to be disposed of at the end of life. Both HTP and the expected quantity of metals and plastics materials disposed of at the end of life are used as indicators for assessment of the social aspect of sustainability. This was a compromise as the initial plan to engage the local stakeholders to identify relevant social sustainability indicators and collect data for these indicators during the project did not materialise. Therefore, better stakeholder engagement in future case studies would enable more socio-economic indicators such as employment, workforce skills development and investment on local market to be identified and used.

2.4 Life Cycle Costing

For the LCC, values were acquired from the ‘BEIS Electricity Generation Cost Report’ of the Department of Business, Energy and Industrial Strategy (BEIS, 2016) and the LCoE for the technologies are shown in Table . The ‘levelised cost’ calculated for each technology “is the ratio of the total costs of a generic plant (including both capital and operating costs), to the total amount of electricity expected to be generated over the plant’s lifetime. Both are expressed in net present value terms.”. This report does not consider potential revenue streams and uses a discounted lifetime (in this case for 20 years) cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWh. The values used refer to the projects commissioning in 2020 and effort was made to match the technologies of the report with those of the case study.

Table 3 Levelised Cost of Electricity of selected technologies

Electricity generation/storage technology	**Wind 300 kW**	**Wind 800 kW**	**Wind 2MW**	**Photo voltaic 3kWp**	**Photovoltaic, 570kWp open ground**	**Tidal turbine 1MW**	**Battery Li-ion 2.1 kWh**

LCoE £ per MWh	145	104	76	103	86	446	425

For all the wind turbines the ‘Onshore wind 100-1500kW’ LCoE values of the report were considered and more specifically for the 300kW wind turbine the High Capex estimate (£145/MWh), for the 800 kW the Central Capex estimate (£124/MWh) and for the 2MW wind turbine the Low Capex estimate (£104/MWh). For the mounted photovoltaic of 3kWp which is used to model the roof photovoltaic installations, the ‘Solar<10kW’ LCoE Low Capex value of the report was considered (£103/MWh) amd for the open ground photovoltaic installation the ‘PV 1-5MW ground’ High Capex vale (£86/MWh). For the Sabella D10 tidal turbine, the ‘Tidal stream’ High Capex estimate for 2025 (£446/MWh) was considered because that was the closest projection value available.

For the diesel generation, an LCoE was not acquired from that report because the capital expenditure has already been realised in the past and only the fuel cost as an operational expenditure was considered. It was estimated that the generators consume approximately 2,000,000 l of fuel per year (Natacha Haas Guégo, 2018). This value was used for the diesel consumption (at a price of £1.05/litre at the time of the study).

Although LCOE is a widely used metric, it cannot reflect adequately the indirect costs and it could be problematic as it does not reflect the differing value propositions of technologies especially. Therefore, value-adjusted LCOE (VALCOE), a metric that considers both cost and value of variable renewables and dispatchable thermal technologies (International Energy Agency, 2020), has started to be used. At the time the research was undertaken we could not find values based on the VALCOE, but this is something that will be improved in the new version of the tool.

The users can overwrite these predefined values at the ‘Input’ sheet of iCELTIC because the various capital and expenditure costs associated with the levelized cost of electricity can change in a volatile economic environment, especially the currency conversion rate. Changes are also expected as the values acquired from the reports refer to estimates based on projections from previous years values. In addition, the proliferation of some of the newest technologies is expected to reduce the costs when economies of scale are achieved. Moreover, the user might need to substitute values with ones quoted by the potential project developers who can get site-specific conditions data.

3 Results and discussion

In this section, the results for the seven scenarios examined for Ushant island are presented and compared to the BAU scenario. The full numerical results and analytical graphs with the contribution per technology are provided in the appendices and supplementary information, and the comparison between the scenarios is given in Figure 2.

3.1 Techno-economic assessment results

3.1.1 Electricity generation

The results show that only three scenarios -S2, S3 and S7 that generate 8,254Wh, 14,686MWh and 9,253MWh respectively- manage to cover the 6,807 MWh per annum set as a threshold by the BAU scenario. Scenario S5 does not qualify but it comes close with 4,888 MWh, while the rest of the scenarios -S1, S4 and S6 that generate 1,696MWh,1,183MWh and 2,182MWh respectively- do not cover even one third of the generation. None of the qualifying scenarios utilises the planned photovoltaics, but rather an extensive solar installation in 20% of the roofs and some sort of wind. The tidal turbine could provide support and reduce the requirement for wind, but it cannot be sufficient without it regardless of the remaining contribution from solar.

The scenarios were based on the three project reports and the combinations include the inputs provided by the stakeholders. The main focus is the decarbonisation and no diesel electricity generation is considered as part of the mix. As one of the criteria set is the ability to satisfy the energy demand using a decarbonised generation mix, the scenarios that fail to pass this criterion are not investigated further and they are not included in the results analyses that follow.

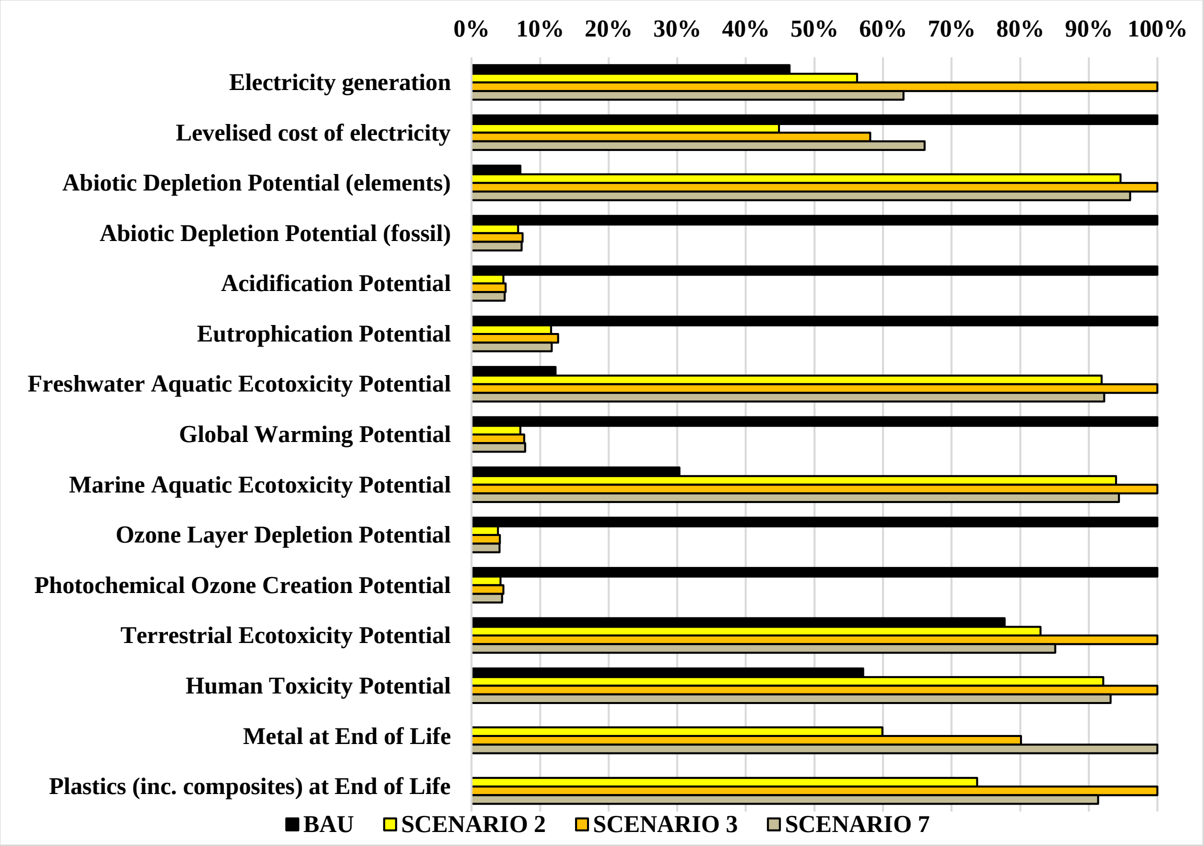

Figure 2 iCELTIC results for Ushant case study

3.1.2 Levelised Cost of Electricity (LCoE)

The cost results show that all scenarios prove to be more economical than the BAU which costs annually £2,100,000. From the three scenarios that cover the demand, S2 shows the lowest cost followed by S3 and then S7. A medium scale wind turbine of 800kW can provide the energy required at the lowest cost without the need to oversize and use a 2MW like S3 or add a tidal turbine to the energy mix like S7.

From both the electricity generation and the LCoE results it turns out that from the techno-economic point of view the best scenario is S2, followed by S3 and S7. This analysis so far has highlighted the importance of the efficiency per unit both technical and economic.

3.2 Environmental assessment results

3.2.1 Abiotic Depletion Potential (ADP elements)

The ADP elements show the decrease of the availability of non-biological resources as a result of their unsustainable use and it is measured in Kg of antimony (Sb) equivalent. The BAU scenario only scores 7.1% of S3 that scores the highest and which is followed by the scenarios that also generate more electricity, and this can be attributed to the higher requirement for device production resources. In addition, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about ten times higher ADP element values per kWh produced than the wind and tidal turbines. The scenario that covers the demand and keeps the ADP elements impacts lower at the same time is S2, followed by S7 and S3.

3.2.2 Abiotic Depletion Potential (ADP fossil)

The ADP elements show the decrease of the availability of non-biological fossil resources as a result of their unsustainable use and it is measured in MJ. The BAU scenario scores the highest by far and then S2, S3, S5 and S7 follow with results ranging from 6.8% to 7.4% of the BAU. In the seven scenarios, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about two times higher ADP fossil values per kWh produced than the tidal turbine and three to five times than the wind turbines. The scenario that covers the demand and keeps the ADP elements impacts lower at the same time is S2, followed by S7 and S3.

3.2.3 Acidification Potential (AP)

The AP shows the reduction of the pH due to the acidifying effects of anthropogenic emissions which is connected to the damage to the quality of ecosystems and decrease in biodiversity and is measured in sulphur dioxide (SO_2) equivalent. The BAU scenario scores the highest by far and then S2, S3, S5 and S7 follow with results ranging from 4.6% to 5% of the BAU. In the seven scenarios, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about four times higher AP values per kWh produced than the tidal turbine and five to seven times than the wind turbines. The scenario that covers the demand and keeps the AP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.2.4 Eutrophication Potential (EP)

The EP shows the accumulation of nutrients in aquatic systems and is connected to the damage to the quality of ecosystems and is measured in kg of Phosphate PO_4^{3-} equivalent. The BAU scenario scores the highest by far and then scenarios S2, S3, S5 and S7 follow with results ranging from 11.2% to 12.6% of the BAU. In the seven scenarios, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about 19 times higher EP values per kWh produced than the tidal turbine and four to six times than the wind turbines. The scenario that covers the demand and keeps the EP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.2.5 Freshwater Aquatic Ecotoxicity Potential (FAETP)

The FAETP shows the toxic effects of chemicals on a freshwater aquatic ecosystem and is connected to the damage to the ecosystem quality and species extinction and is measured in kg 1,4-dichlorobenzene equivalent (1,4-DB). The BAU scenario only scores 12.3% of S3 that scores the highest and which is followed by the scenarios that also generate more electricity, and this can be attributed to the higher requirement for device production resources. In addition, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about 37 times higher FAETP values per kWh produced than the tidal turbine and three to seven times than the wind turbines. The scenario that covers the demand and keeps the FAETP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.2.6 Global Warming Potential (GWP 100 years)

The GWP shows the alteration of global temperature caused by greenhouse gases and is connected to the damage to biodiversity decrease in general, temperature disturbances and climatic phenomena abnormality (e.g. more powerful cyclones, torrential storms, etc.). It is measured in kg carbon dioxide equivalent CO2-eq. The BAU scenario scores the highest by far and then S2, S3, S5 and S7 follow with results ranging from 7.1% to 7.8% of the BAU. In the seven scenarios, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about two times higher GWP values per kWh produced than the tidal turbine and three to six times than the wind turbines. The scenario that covers the demand and keeps the GWP impacts at the lowest possible level simultaneously is S2, followed by S3 and S7.

3.2.7 Marine Aquatic Ecotoxicity Potential (MAETP)

The MAETP shows the toxic effects of chemicals on a marine aquatic ecosystem and is connected to the damage to the ecosystem quality and species extinction and is measured in kg 1,4-dichlorobenzene equivalent (1,4-DCB). The BAU scenario only scores 30.3% of S3 that scores the highest and which is followed by the scenarios that also generate more electricity, and this can be attributed to the higher requirement for device production resources. In addition, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about 34 times higher MAETP values per kWh produced than the tidal turbine and five to seven times than the wind turbines. The scenario that covers the demand and keeps the MAETP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.2.8 Ozone Layer Depletion Potential (ODP)

The ODP shows the diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone depleting substances and is connected to the damage to the ecosystem quality and human health and is measured in kg trichlorofluoromethane R-11 equivalent. The BAU scenario scores the highest by far and then S2, S3, S5 and S7 follow with results ranging from 3.9% to 4.2% of the BAU. In the seven scenarios, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about three times higher ODP values per kWh produced than the tidal turbine and five to eight times than the wind turbines The scenario that covers the demand and keeps the ODP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.2.9 Photochemical Ozone Creation Potential (POCP)

The POCP shows the type of smog created from the effect of sunlight, heat and NMVOC and NOx and is connected to the damage to the ecosystem quality and human health and is measured in kg ethylene equivalent. The BAU scenario scores the highest by far and then S2, S3, S5 and S7 follow with results ranging from 4.2% to 4.7% of the BAU. In the seven scenarios, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about three times higher POCP values per kWh produced than the tidal turbine and three to five times than the wind turbines. The scenario that covers the demand and keeps the POCP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.2.10 Terrestrial Ecotoxicity Potential (TETP)

The TETP shows the toxic effects of chemicals on a terrestric ecosystem and is connected to the damage to the ecosystem quality and species extinction and is measured in kg 1,4-dichlorobenzene equivalent (1,4-DCB). The BAU scenario is the fourth worst and scores 77.7% of S3 that scores the highest and which is followed by the scenarios that also generate more electricity. In addition, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops but this time the difference with the other scenarios is not so great because the roof mounted photovoltaics have about four times higher TETP values per kWh produced than the tidal turbine but they have up to three times lower values than the wind turbines. The scenario that covers the demand and keeps the TETP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.3 Social assessment

The social part of the assessment includes the HTP and the Metals and Plastics disposed at the end of life. Other LCA impacts could also be included here such as POCP, ODP etc as their damage is not only to the ecosystem but also to human health but the HTP is the one that has an impact to the human health exclusively.

3.3.1 Human Toxicity Potential (HTP)

The HTP shows the toxic effects of chemicals on humans and is connected to the damage to human health and is measured in kg 1,4-dichlorobenzene equivalent (1,4-DCB). The BAU scenario is the fifth worst and scores 57.1% of S3 that scores the highest and which is followed by the scenarios that also generate more electricity. In addition, the technology installation that contributes the most is the extended photovoltaic on 20% of the suitable rooftops which is expected up to a point because the roof mounted photovoltaics have about 12 times higher HTP values per kWh produced than the tidal turbine and two to four times than the wind turbines. The scenario that covers the demand and keeps the HTP impacts at the lowest possible level simultaneously is S2, followed by S7 and S3.

3.3.2 Metals at End of Life

The metals at the end of life do not constitute a standardised metric like the life cycle impact categories presented before. Nevertheless, as metals can be a material that has a high recyclability and value recovery attributes it can be quite beneficial to the stakeholders to have an overview of the expected disposed metals at the end of the device's lifetime. On the other hand, they still constitute a waste material that must be collected and managed appropriately. The scenarios that score higher are the ones that also generate more electricity, and this is expected as more resources would be required for that to create more devices. Scenario S7 scores the highest and S5 follows. This time the third position is for S6 and not S3. This is because the technology installation that contributes the most is the tidal turbine which is expected up to a point because it has about five times higher values per kWh generated than the photovoltaic and three to six times than the wind turbines. The scenario that covers the demand and keeps the mass of the disposed metals at the lowest possible level simultaneously is S2, followed by S3 and S7.

3.3.3 Plastics (inc. composites) at End of Life

The plastics like the metals at the end of life do not constitute a standardised metric like the life cycle impact categories presented before. Unfortunately, the plastics so far are not like metals that can be a material that has a high recyclability and value recovery attributes. However, even as a form of a difficult to handle and extract value waste knowing their mass is quite beneficial to the stakeholders to have an overview of the expected disposed plastics at the end of the device's lifetime. The scenarios that score higher are the ones that also generate more electricity, and this is expected as more resources would be required for that to create more devices. Scenario S3 scores the highest, followed by S7. Although the technology installation that contributes the most is the roof mounted photovoltaics, the tidal turbines has about two times higher values per kWh generated than the photovoltaic and three to seven times than the wind turbines. The scenario that covers the demand and keeps the mass of the disposed plastics at the lowest possible level simultaneously is S2, followed by S7 and S3.

4. Discussion

Ushant island has been a useful example because it is a real case were the transition to renewables and detachment from fossil fuels must be materialised. The nature of this island did not allow for the use of other models which although more comprehensive and useful on a national level cannot be used in the cases of smaller remote areas that are not connected to the grid. The scenarios examined were based on actual data resource assessment that took place and that guarantees the credibility and representativeness of a remote island case. Summary results on the case study of Ushant show that there are scenarios that can reduce all the scores for the impacts of the sustainability indicators and therefore utilise renewables and achieve an improved sustainability from a lifetime perspective. However, only scenarios S2, S3 and S7 can achieve the same level of electricity and they score lower than the BAU scenario for all categories except the ADP elements and the freshwater, human, marine and terrestrial ecotoxicity. Comparing the scenarios with each other, it is shown that S2 generates the required amount of electricity while keeping the rest of the impacts at the lowest possible level followed very closely by S7 and S3. Scenario S2 is the scenario that utilises an extensive use of photovoltaics and a medium size wind turbine and this could send a message that appropriate sizing and especially avoiding oversizing is of the essence. In addition, the results can highlight the need for an infrastructure that can secure the electricity provision, and this is important as a reality check of new promising but not mature yet technologies. Finally, the results can reveal the trade-offs that exist when trying to achieve many technoeconomic, environmental and social goals.

To the best of the authors' knowledge, policy makers in Ushant have not yet adopted the results of this work at the time of writing. Stakeholders that could affect policy making (such as major electricity providers) showed interest in the tool but the consideration of the LCA impacts was not a priority. This limited stakeholder engagement in the case study is also a limitation for this work. Other limitations are the use of the LCOE instead of the more up-to-date VALCOE and the small set of social indicators. These limitations can form the basis for future improvement.

5. Conclusions

The LCSF is an easy to implement framework and utilising the iCELTIC interface in Excel can relieve the remote island stakeholders from the need to engage in a set of costly and timely analyses because, once set up for the specific area, there is no need to commission a large number of studies every time their preferences change. The results from our study can be made accessible in an Excel tool that the stakeholders/users can use to assess and design their own energy systems. The results of the Ushant case study show that only three out of the seven examined renewable energy scenarios manage to cover the 6,807 MWh per annum demand. These scenarios can improve all the indicators against the business-as-usual diesel generation scenario except the ones related to toxicity and reduce greenhouse gas emissions by more than 92%. The users can simply change the configuration and investigate as many scenarios as they would like until they find the most sustainable one. This can assist with the transition to an affordable, low carbon renewable energy mix without hiding at the same time the potential impacts to human health and the expected waste at the end of life. In the future the LCSF method and iCELTIC can be updated to include more technologies and support the investigation of more sustainable energy scenarios of other remote island cases.

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