Energy Proceedings
Vol 31, 2023
ISSN 2004-2965

Techno-Economic Study of a Distributed Renewable Power System for an Island

Chris Atkinson[1], Yaodong Wang[1*]
1 Department of Engineering, University of Durham
Durham, DH1 3LE, United Kingdom

ABSTRACT

The focus on the reduction of emissions and the transition away from fossil fuels has been growing, especially in recent years. This is of the utmost importance on islands where the impacts of climate change are most threatening and where the main source of energy has been found to come from the burning of fossil fuels. Thus, the feasibility of implementing a distributed renewable energy system has been investigated for a set of islands off the coast of the UK. Three systems and their technical and economic feasibility were analysed using a software designed in Excel with one system having net zero emissions.

Keywords: Renewable Energy, Penetration Levels, Climate Change and Net-Zero Emissions

NONMENCLATURE

Abbreviations

LCOE	Levelized Cost of Energy
NPV	Net Present Value

Symbols

A	Turbine Swept Area	ρ	Fluid Density
C_p	Performance Coefficient	v	Fluid Velocity
I	Initial Investment Cost	F	Fuel Cost
O	Operation Cost	d	Discount Rate
M	Maintenance Cost	E	Energy Produced
N	Lifetime	n	year

1. INTRODUCTION

With climate change continuing to worsen, the issue of global warming remains a key priority of governments worldwide. In 2019 alone, net territorial emissions in the UK stood at 454.8 million tonnes, with 80% of this being CO2, and with global electricity needs set to increase by 2.1 percent each year, this figure is only set to increase. This has been recognised by the UK Government who set the target of reducing emissions by 100% by 2050, thus causing a drive in demand for new renewable technologies which has greatly impacted the respective cost of electricity produced. It was even found by Roser (2021) that the cost of some forms of renewable energy are now outcompeting the more commonly used fossil fuels, with wind and solar being over half the price of coal [1]. This is due to renewable energy following a learning curve such that when the quantity of installed renewable technology doubles, the price of the energy halves.

With global temperatures rising and an estimated 750 billion tonnes of ice melting each year, Islands are an area that will be especially impacted. They are also an area where a transition to renewable energy could be increasingly effective, as the majority are still currently powered by diesel generators. Dalton et al (2019) recognised that the best way to transition was through the implementation of a hybrid energy system as this would increase the reliability of the system - eliminating this key issue that comes with renewable energy [2].

There are numerous different forms of energy that could be used to create a hybrid energy system. Findings from both Miao (2020) and Robinson (2019) have shown that due to eastward moving Atlantic depressions bringing strong winds throughout the year, the UK is in an optimal position to utilise wind energy [3][4]. Solar Energy also has a large potential in the UK. A review of previous work by Herrando et al (2016) indicates that Photovoltaic-Thermal Panels (PVT) are the most efficient method of solar energy production [5]. These are more efficient than standard Photovoltaic Panels (PV) as at a reduced temperature, the current in the panels will decrease and the voltage will increase. However, the voltage increases at a faster rate than the current decreases, resulting in an increased energy output and efficiency.

Waves and Tidal Streams also provide a potential source of energy. These are relatively immature forms of energy production and so are generally more expensive. The cost is also impacted by the location, with some being unsuitable due to unfavourable conditions. However, they do have the potential to provide a reliable energy supply – something other renewable energy struggles with. Anaerobic Digestion also provides a reliable energy supply. This is a biochemical process used to obtain biogas fuel from organic waste material which can then be used to produce energy. This thereby has the benefit of reducing the waste going to landfill, whilst also producing electricity.

The reliability and variability of renewable energy from an output standpoint, is one of the biggest issues it faces. However, with the implementation of effective storage techniques, this can be resolved. Findings by Blechinger (2014) show that by using a battery storage system on an island, the renewable penetration level can be increased by 25%, showing its effectiveness [6]. Hydrogen also provides an alternative storage technique and can smooth the fluctuations in renewable energy, producing a more consistent supply of energy.

Although there are numerous research papers and developments of renewable energy systems for islands, none can provide 100% of power supply to replace fossil fuel completely. It is therefore necessary to carry on research into this area to find 'net-zero' solutions. The aim of this study is to investigate and find feasible solutions for islands using a case study in the UK.

2. METHODOLOGY

Situated 50km off the South-Western tip of Cornwall, the Isles of Scilly were chosen for the feasibility analysis. The islands current only form of connection to the UK's national grid is via a 33kW, 55-kilometre subsea cable which links the largest island to Cornwall. A network of 11kW subsea cables then connect the other 4 inhabited islands. However, the network is known to be unreliable and in March 2017, a fault resulted in the islands having to rely solely on the backup diesel generators for power for two weeks. It was found that the Islands currently have nine 160kW diesel generators which have an estimated full load fuel consumption rate of 40 litres per hour. As a result, approximately 0.48kt of CO_2 was released in this two-week period. There are two potential solutions that could be implemented to solve this issue: lay a new cable or a new energy system.

Whilst providing a reliable energy source, the economic and environmental cost of laying a new cable is incredibly high. Renewable Energy on the other hand poses a potential solution to the issues a new cable has and would enable the islands to utilise the vast potential they have when it comes to green energy. This will help push the islands towards meeting green energy targets and could be used by the UK government as an example that other such communities should follow.

2.1 *Data Collection*

2.1.1 Energy Demand

The year 2019 was chosen as the focus of the study as this was the last full year before the COVID 19 outbreak and so will be a more reliable representation of the yearly energy demand that can be expected. Through research, it was found that electricity is the sole form of energy used for both power and heating. This electricity demand fluctuates throughout the year as displayed in figure 1 and costs approximately £3,500,000 (calculated using a tariff from the energy provider Bulb).

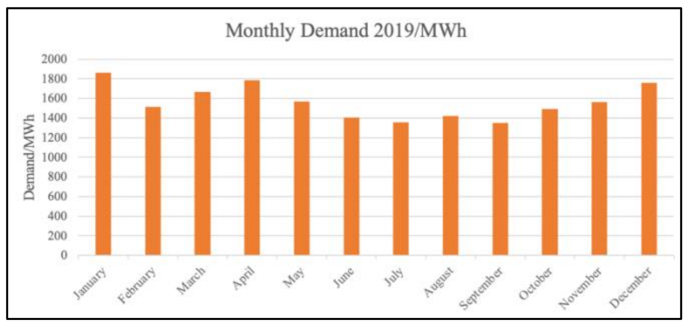

Figure 1: the monthly demand of the Scilly Isles

The demand can be seen to reach its peak during January and December which is caused by the large winter storms that the island experiences. Another peak can also be seen in April as this is when holiday homes are prepared for the tourist season, resulting in a larger heating demand and therefore energy consumption.

2.1.2 Weather Data

To determine the renewable energy capability, weather data from 2019 was collected. It was found the average wind speed was 7.6m/s, almost twice as high as the UK average (4.2m/s). It was also shown that the islands experience 280 hours more sunshine per year than London showing the potential the islands have for implementing renewable energy

2.1.3 Other Data

To calculate the potential output of an anaerobic digestion plant, waste data was needed. Only a comprehensive breakdown of the waste from 2014 was found and so an assumption was made that the percentages of each category remained the same, enabling an estimated composition to be found since 1640 tonnes of waste was produced in 2019.

3. MODELLING AND SIMULATION

The software used in this project was created to analyse the impact a renewable energy system would have if implemented in a certain situation. It works by splitting the system up into its individual components before calculating the renewable energy that can be produced and then combining them back into the original system where the software calculates the amount of energy that is needed, stored, or lost at a certain time of day. If any additional energy is needed, both diesel generators and grid energy can be tested to analyse the impact. To make the software work, the following calculation processes were used:

3.1 Renewable Energy Equations

3.1.1 Wind and Tidal Stream

Wind and Tidal Stream work in similar ways due to their use of turbines and so are calculated similarly:

$$P_{available} = 0.5\rho A v^3 C_p \quad (1)$$

The coefficient of performance changes for each turbine model and is found through the analysis of power curves. As part of the wind turbine, a pitch angle controller is used to limit the speed of the wind turbine when the wind speed exceeds the cut out speed.

3.1.2 Solar

The model implemented in the software follows the calculation process and findings of Duffie and Beckman (1991). This process finds the cell temperature under the changing solar irradiance and ambient temperature before being used to find the power output [7].

3.1.3 Wave

To find the potential wave energy resource, findings from Abramowitz and Stegun (1965) are used. This process calculates the wave group speed and thus the power at different wave depths, with the Newton Raphson Method being used in transitional waters [8].

3.1.4 Hydrogen

To ensure the production of green hydrogen, renewable energy will be used to power an electrolysis plant. This process is 81% efficient and so 48kWh will be needed to produce 1kg of hydrogen. However, the storage process is only 69.4% efficient as only 33.33kWh can be extracted per kilogram.

3.1.5 Anaerobic Digestion

To calculate the AD potential, waste data is used to determine the quantity of substrate that can be used. It was found that materials such as paper and organic waste can be used in the plant as well any dry digestate from sewage. The tonnage of this usable waste can then be used to determine the time frame when the plant can be active and thus the amount of energy that can be produced.

3.1.6 Battery Energy Storage System (BESS)

These individual energy outputs are then combined into a whole configuration, where a BESS can be implemented. This will ensure a smooth and stable power supply and will maximise the amount of energy that can be utilised. The software uses Lithium-Ion Batteries as the basis for the system. The lifetime of this type of battery decreases when it is at an extreme state of charge (SOC). Therefore, to reduce the rate at which the battery degrades, its state of charge is kept between 20% and 80%. If the battery is at a low SOC and additional energy is needed to meet the demand, the stored hydrogen is utilised.

3.2 Economic Viability Equations

The software also calculates a break-even point through looking at the NPV and the respective yearly savings generated through a systems implementation.

3.2.1 Levelized Cost of Energy

A good indicator used to evaluate renewable energy technology is the LCOE. This is the NPV at which the energy needs to be sold to break even in its lifetime.

$$LCOE = \frac{\sum_{n=0}^{N}\left(\frac{I_n + O_n + M_n + F_n}{(1+d)^n}\right)}{\sum_{n=0}^{N}\left(\frac{E_n}{(1+d)^n}\right)} \quad (2)$$

3.3 Validation

To ensure the outputs from the software are technically astute, validation took place by comparing the outputs to their respective commercially available data. This can be seen in table 1 which shows how the software compares to the online database:

	Wind	Solar	Wave	Tidal
Manufacturer Data/ GWh	3.597	0.300	2.000	0.773
Simulation Results / GWh	3.642	0.297	2.013	0.701
Difference/ %	**1.667**	**1.251**	**0.629**	**8.992**

Table 1: the Renewable energy systems tested by the software

Tidal energy has a large error due to a severe lack of data, as only values for the average Neep and Spring Tidal Currents were found for the Scilly Isles. Therefore, the program is not as accurate, as it makes it difficult to precisely estimate hourly variation.

3.4 Design of Systems

Through the testing of numerous different configurations and analysing the impact of including specific systems, three systems were created:

Resource	Option 1	Option 2	Option 3
Wind	5MW	4MW	3MW
Solar Panels	4MWp	3MWp	1MWp
WEC	Yes	No	No
Tidal	No	No	No
Hydrogen	1MW	0.5MW	No
AD	0.5MW	0.5MW	0.5MW
Battery	40MW	20MW	10MW

Table 2: the Renewable energy systems tested by the software

A schematic of the system and how the renewable energy would be integrated into the current system can be seen in Figure 2.

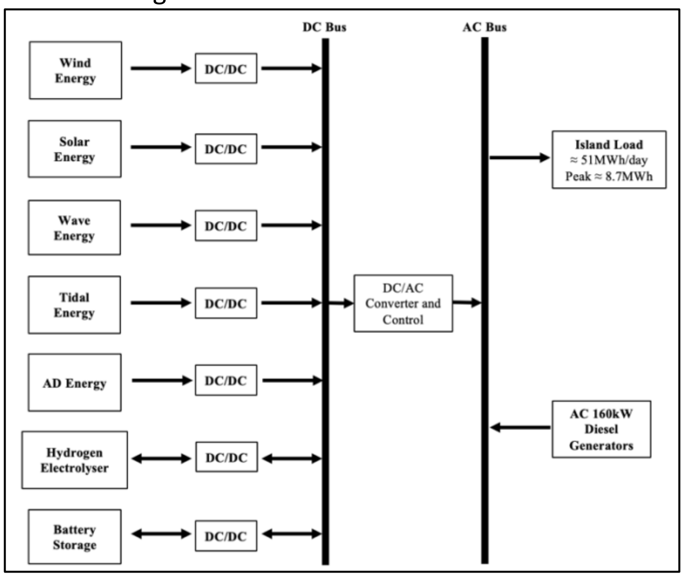

Figure 2: a schematic of the whole renewable energy system

For the analysis it has been assumed that all the renewable energy systems are implemented at the same time. This would not happen in the real case as it is more likely that the system is set up over several years due to the initial system and installation costs and time. As well as this, any additional energy is supplied by the diesel generators.

4 RESULTS AND DISCUSSION

4.1 Technical Analysis

The technical results for each of the systems can be seen in Table 3:

Resource	Option 1	Option 2	Option 3
Energy Produced GWh	33.56	21.56	14.81
Additional Energy GWh	0.75	3.44	5.89
Emissions Reduction %	89	60	33

Table 3: the technical results from the simulation where additional energy is supplied by diesel generators

4.1.1 Electrical Energy Production

It was found Option 1 performed the best at meeting the demand with only 0.75GW of additional energy needed. However, 21% of the energy that this system produces is lost due to a lack of storage and the variation in demand, thus causing its overall system efficiency to be low. Upon analysis of when more power was needed, it was found that 75% was required in January. This was due to the weather conditions in this month not being suitable for renewable energy, as well a large demand. This can be seen in Figure 3 which shows the number of days that additional power was needed each month for the three systems.

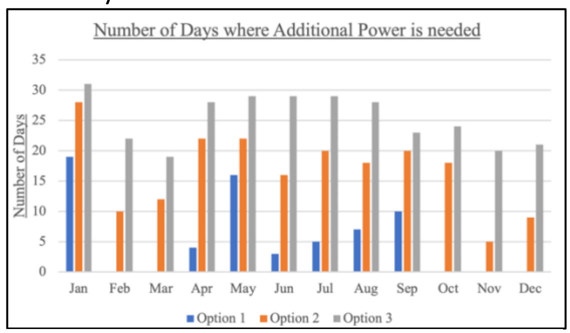

Figure 3: the number of days where additional power is needed for the island

Option 1 is seen to be the most beneficial in terms of additional power needs. When the simulation was continued into 2020, no additional power was required as the supply was met fully, thus making it a net-zero system. This can be explained by the reduced energy demand due to the COVID-19 pandemic and because a small amount of hydrogen had been built up as backup storage, something that was not present the year prior.

Due to the lack of renewable energy systems included in Option 3, only 12.86GWh of useful energy could be produced – the lowest of the three systems. This is significantly below the demand for the islands and so nearly a third of the demand would need to be met through other means. As seen in Figure 4, this system performs especially poorly during peak demands due to the limited storage it has.

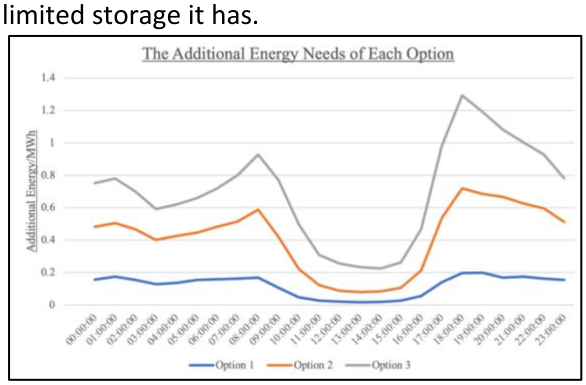

Figure 4: the additional energy needs of each system

4.1.2 Carbon Emissions

As most islands are powered by diesel generators, the software compares the designed systems to both the current system (combination of grid and diesel) and an entirely diesel system. It was found that the entirely diesel system emits 12.552kt of CO2 per year whereas the current system emits 5.98kt, a 52% improvement.

Option 1 was found to be the most beneficial from an emission standpoint, with the minimal emissions occurring when the grid was used as the backup energy supply. This resulted in a decrease of 89% from the current emissions and 95% from the full diesel system. When the simulation was continued into 2020, no additional power was required, thereby achieving a net zero emissions system. Option 3 was found to be the worst from an emission standpoint. This was down to the large amount of additional energy needed to meet the demand, resulting in large amounts of emissions, especially when diesel generators were used as the source. However, despite this, option 3 still proved better than the current system in place with a reduction of 33% occurring at the very least.

4.2 Economic Analysis

Whilst the technical analysis showed how effective each system was at meeting the demands of the island, it did not show how viable they would be for the island. This is an important factor as the Islands do not have substantial funds and so the economic results are important in determining the most feasible system.

4.2.1 Levelized Cost of Energy

As seen in table 4, the LCOE of each of the renewable energies was found with wind and solar being the most financially viable options for renewable energy. This is because the focus on this technology has been large, allowing technological advances to occur, thus reducing its cost. This is not the case with Wave and Tidal which are in their infancy by comparison with Tidal being nearly twelve times more expensive than Diesel Energy, hence its exclusion from the three configurations.

Wind	Solar	Wave	Hydrogen	Tidal	Diesel	AD
£53.48 /MWh	£75.90 /MWh	£216.67 /MWh	£187.57 /MWh	£1855 /MWh	£153.13 /MWh	£98.82 /MWh

Table 4: the LCOE for each renewable technology and Diesel in 2019 when red diesel was priced at 61.19p/litre

To ensure the cost analysis was fair and the whole system was analysed, the cost of any additional energy needed was included in the overall system cost, and only the useful renewable energy produced was included in the calculations. When this was done, Option 3 performed best with an LCOE of 109.81 £/MWh. This was due to its inclusion of only wind and solar technology and limited battery storage which thus reduced the initial cost of the system. Option 2 also performed better in comparison to diesel with an LCOE of 127.59 £/MWh. However, Option 1 performed worse (174.97 £/MWh) due to its inclusion of wave energy and a large amount of battery storage. It was found that this option would only perform better when the cost of diesel exceeded 71p/litre. It should be noted that this simulation uses the diesel generators to produce the additional energy needed to meet the demand. In retrospect, this is likely to come from the grid instead. As a result, when the simulation was run again but with the grid supplying the additional energy, the LCOE's for Option 1, 2 and 3 were 178.71 £/MWh, 135.16 £MWh and 121.99 £/MWh respectively. An increase in levelized cost can be seen for all options. This was because when the grid is used, there is a standard daily charge from the energy supplier which across a whole year and for all islands, would amount to approximately £87,000.

4.2.2 Break Even Point

The Break-Even Point describes the number of years needed to recover the project costs. It considers the lifetime system cost and the relevant savings its implementation would have on the yearly energy bills from the island and can be seen in Figure 5 where the net income of each project can be seen. Decreases in the net income of each system can be seen between years 10 and 11 as this is when the battery systems are replaced due to their lifespan of 10 years.

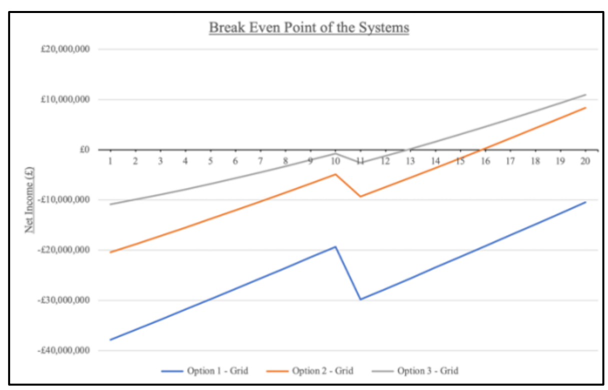

Figure 5: the net income from the three systems

As can be seen, Option 3 has the shortest break-even point of 13 years, followed by Option 2 which is 16 years. The break-even point for Option 1 is beyond that of the systems lifetime due to the increased battery storage. This increased the systems capital investment across its project lifetime, causing it to not reach profitability, therefore showing that it is not economically feasible.

It should be noted that the values found in the above analysis imply that the systems are all funded by the island and that no loans or borrowing occurs. If this were not the case, the amount of interest amassed by the project, and thus additional costs, would need to be included which would drive the break-even point up.

4.3 Discussion

It has been found that Option 1 was the best from a technical viewpoint with the largest decrease in emissions and the lowest additional energy needs. However, it was not economically feasible as its break-even point was beyond that of its lifespan. Option 2 was financially more viable and was able to reach profitability before the end of its lifespan. However, it could not meet the energy demands of the island with renewable energy alone and so would require a grid connection to ensure this happened. This was better both economically and from an emission standpoint than using diesel to provide the necessary additional energy. Option 3 performed best economically out of the three options, with the shortest payback period and smallest LCOE. Much like option 2, this system requires a grid connection to ensure the islands demand is met. Because of this, and the fact that this option had the highest additional energy needs, the reduction in emissions was smallest.

However, due to the Scilly Isles size and lack of financial backing, option 3 would be best in the short term. This is due to the reduced initial cost as well as the reduced break-even year. By implementing this renewable system, it would also give the island the opportunity to expand further in the future without such a large economic impact, enabling a transition to the configuration seen in Option 2. If this were the case, it has been calculated that if the system were to be upgraded in the 11th year after implementation, it would reach profitability by year 19. This would thereby be beneficial to the island as it would decrease the initial cost, whilst providing the island with a plan and the infrastructure to achieve net zero emissions.

5 CONCLUSION

This feasibility study has shown that a distributed renewable energy system is able to meet the energy demands of a large island community. Option 1 was able to meet the energy demands of the island in the years following its implementation, removing the need for grid/diesel energy thereby making it net-zero. However, it was found implementing this solution was not economically viable as profitability was not reached.

Consequently, Option 3 would be the most ideal system to be implemented with an upgrade to option 2 occurring once its break-even point is met. This would result in a significant reduction in emissions once this has been implemented, whilst reducing the economic burden to the islands from a large initial cost.

This study has thus demonstrated that installing a distributed renewable energy system on a large island can meet the energy demand and is a viable alternative to fossil fuel derived energy from the grid or from diesel generators. It also supports and enhances previous research but demonstrates that renewable energy can be used on much larger islands and can feasibly make them net-zero and off-grid. As a result, it shows that this is a potential long-term solution for the negative impacts islands are contributing to climate change and shows that net zero systems can be designed.

ACKNOWLEDGEMENT

The author would like to thank Durham University for the support to attend the Applied Energy Symposium 2022: Clean Energy towards Carbon Neutrality (CEN2022).

REFERENCE

[1]- Roser, M., (1 December 2021), *Why did renewables become so cheap so fast?,* (Accessed 10 January 2022). [Online]. Available: https://ourworldindata.org/cheap-renewables-growthnote-26

[2]- Dalton, G.J., Lockington, D.A., Baldock, T.E., *Case study feasibility analysis of renewable energy supply options for small to medium-sized tourist accommodations*, Renewable Energy, vol 34(4), pp. 1134-1144

[3]- Miao, C., *Techno-economic analysis on a hybrid power system for the UK household using renewable energy: A case study,* Energies, vol 13, p 3231, 2020

[4]- Robinson, S., *Feasibility study of integrating renewable energy generation system in sark island to reduce energy generation cost and CO2 emissions,* Energies, vol 12(24), p 4722, 2019

[5]- Herrando, M., Markides, C.N., *Hybrid PV and Solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations,* Applied Energy, vol 161, pp. 512-532, 2016

[6]- Blechinger, P., *Assessment of the global potential for renewable energy storage systems on small islands,* Energy Procedia, vol 46, pp 294-300, 2014

[7]- Duffie, J.A., Beckman, W.A. *Solar Engineering of Thermal Processes,* John Wiley and Sons inc, 2013

[8]- Abramowitz, M. and Stegun, I.A. (1965) Handbook of Mathematical Functions. Dover Publications Inc., New York