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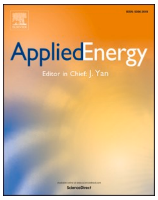

A distributed renewable power system with hydrogen generation and storage for an island

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ABSTRACT

This study aimed to find a distributed renewable power system with hydrogen generation and storage to meet the current Isle of Rum's energy demands. Five different systems (Case 2–6) were evaluated compared to the current power system (Case 1), with the inclusion of a hydrogen generation and storage subsystem acting as an energy storage medium in Case 3, 4, 5 and 6. Case 2 exhibited a 96.2% reduction in diesel consumption. Case 3 and 4 achieved a fully renewable generation mix through the addition of a hydrogen subsystem comprised of a 28 kW PEM electrolyser, 120 kg compressed storage and modified gen-set. Case 5 and 6 also achieved a fully renewable generation mix, meeting the domestic heating and full heating demands of the island respectively through the integration of heat pumps. Economic analysis showed that Case 2 exhibited the lowest cost, with a LCOE of £3.02/kWh, a 43% reduction from Case 1. Both Case 3 and Case 4 also had a lower LCOE than Case 1 of £5.02/kWh and £4.37/kWh respectively. This shows that the hydrogen subsystem designed can be an economically viable option despite its currently high CAPEX. Both Case 5 and 6 had the highest CAPEX of all systems, due to the additional generation technology required to meet the additional heating demand. However, they achieved the lowest LCOE at £1.86/kWh and £0.76/kWh, due to the high efficiency exhibited by the heat pumps used for the heating load.

1. Introduction

The UK, in particular Scotland, has multiple off grid islands. Eales et al. [1], identified 7 off-grid islands or communities currently in place in Scotland, making up a significant proportion of the 49 inhabited Scottish islands. All 7 of these off-grid islands have their own power systems comprised of one or a combination of solar, wind, hydro and diesel generation technologies and at present several technical challenges still exist for the power systems on all these islands [1]. For this case study, one of these islands, the Isle of Rum, was selected due to its current energy system supplying a significant proportion of its demand with diesel generators – the Clean Energy for EU Islands Secretariat in 2020 found that 58% of Rum's total annual energy consumption was supplied by diesel generators [2].

At present, the island has a power system comprised of two hydro-electric generators, a backup diesel generator and a battery bank with an inverter system for grid connection. The system has been in place for many years and has been unreliable in producing fully renewable energy for prolonged periods of time. Therefore, the Isle of Rum would see benefit from a new proposed distributed renewable power system on the island by reducing carbon emissions from diesel consumption. This report entails an investigation into the current energy demands and the natural resource availability of the Isle of Rum, which are used to develop multiple renewable power system designs utilising the current island system as a baseline for improvement. The power systems designed incorporate the use of multiple renewable generation technologies in addition to a novel hydrogen generation and storage subsystem, which aims to reduce and eliminate the need for diesel generators on the island, thereby reducing environmental impact from carbon emissions.

1.1. Distributed renewable power systems

A distributed renewable power system is made up of several components – the term ‘renewable’ refers to a primary, domestic, and clean or inexhaustible energy resource [3]. The term ‘distributed’ refers to distributed generation (DG), which is defined as any source of electric power that is directly connected to the power system distribution

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network [4]. Remote areas such as small islands are often not connected to mains power supply when geographic constraints make it impractical, or when the population is too small for grid connection to be economically feasible [5,6]. Therefore, distributed renewable power systems make an ideal alternative for providing power supply to the island's inhabitants without relying heavily on fossil fuels. The topic of distributed renewable power systems for islands and other remote areas has been investigated with a number of case studies and real world implementations existing today.

One such scheme has been implemented on The Isle of Eigg, a remote island off the north-west coast of Scotland (near to the Isle of Rum). The renewable energy system in place on Eigg is comprised of hydroelectric, solar PV and wind turbines, as well as a backup diesel generator with a battery bank storage system [1]. Chmiel et al. [7], conducted analysis into the power system in place on Eigg, confirming it is possible to supply electricity reliably from a hybrid off grid system – resulting in a 90% renewable energy usage on an annual basis. However, the backup diesel generator was still in use 10% of the time, indicating an opportunity for improvement. It is also important to note that the study [7] only analysed Eigg's electrical demand. Breen [8], confirmed that the Isle of Eigg does not utilise electrical heating other than as a heat dump during excess generation – it is clear that this is an improvement area for off grid power systems.

The importance of generation technology selection and combination is also highlighted in various studies. Aberilla et al. [9] conducted analysis into the feasibility of off-grid energy systems for remote prototypical rural communities in the Philippines by simulating 15 microgrid system configurations.

The analysis confirmed that it is feasible for a hybrid system to meet energy demand at both a household and community scale, and in ideal cases, without the need for a diesel generator. Hybridisation (using multiple technologies as an integrated power system [10]), was found to reduce environmental impacts of off-grid electricity by up to 40% relative to the equivalent from separate installations. He et al. [11] observed similar results through a case study of the Huraa Island of Maldives - concluding that hybridisation of energy resources provides higher system reliability and a cleaner, more efficient power supply. The study also found that utilisation of energy storage systems improve the operation of diesel generators by reducing the required operating hours by 50% and fuel consumption by 30%. Siddaiah [6], also addresses the importance of optimal selection and sizing of hybrid renewable energy systems. Economic based models revealed that optimal system sizing helps achieve the lowest cost, arrived at by considering the overall cost incurred over the operating life of the power system. These studies support claims of hybrid renewable energy system based power generation being feasible from both a technical and economic perspective for remote islands, akin to the Isle of Rum.

1.2. *Hydrogen generation and storage*

The topic of hydrogen being used as an alternative fuel to traditional fossil fuels has been studied by many authors in an aim to establish it as a viable clean energy source. It is worth noting that hydrogen itself is not a primary energy source, instead it is regarded as a secondary 'energy carrier', as it is first produced using energy from another source before being stored or transported for later use, at which point its latent chemical energy can be realised for energy production [12]. In order for hydrogen to be considered a 'green' fuel source, the energy used to generate the hydrogen must be that of a renewable energy source [13].

For the application of renewable power systems for remote islands, this means that it could be feasible to produce hydrogen during periods of excess energy generation from other renewable sources (such as wind or solar), which could then be stored. This stored hydrogen could then be used as a backup energy system during periods where the output from other renewable sources falls short of the immediate system demand. In doing this, the need for a diesel generator would be alleviated and the possibility of a fully renewable system would be observed. Edwards et al. [12] identified this, stating that hydrogen can be used as a storage medium for electricity generated from renewable resources, providing a solution to the issue of intermittency of supply in renewable power systems. One study investigates this idea through a case study of an existing power system in place on the Isle of Eigg, Scotland. As mentioned earlier, from [7], the diesel generators on Eigg are still used relatively frequently to supplement renewable generation. Kennedy et al. [14] investigated using hydrogen generated from additional wind turbines to replace diesel as the fuel for the backup generator, i.e. a subsystem of renewable hydrogen generation. It was found that an additional four 20 kW turbines on the island would produce 3260 kg/year of hydrogen, which was more than sufficient to meet the annual demand (1890 kg/year) necessary to use hydrogen as a backup fuel replacement. This indicates that it is theoretically feasible to use this method to replace diesel with hydrogen generated from a sub-system within a renewable power system on an island. Lin et al. [15], studied a large wind- solar-hydrogen multi-energy supply (output over 15,000 MWh per month) system, using hydrogen as the storage medium, to provide smoothing power supply. They found that system has the potential to produce 931.39 kg of hydrogen per year, with the levelized cost of energy (LCOE) of 0.2755 $/kWh (£0.2247/kWh), and the payback time is approximately 3 years. Meng et al. [16] studied a wind-hydrogen coupled energy storage power generation system (two 1.5 MW wind turbines, electrolyser, hydrogen storage tank, etc.) to meet electricity demand which is about 1833.3 kWh/h. The results from their study showed that the system can produce 12.31 kg and consume 8.62 kg hydrogen in one hour, and the system can meet the dynamic electricity demand. The cost of the hydrogen system is ¥2347,681 (£261,678) payback time is 15.3 years.

A real-world implementation similar to this methodology has taken place on the Orkney Islands, a remote archipelago off the north-east coast of Scotland. The scheme in place on Orkney utilises curtailed wind turbine electricity by converting it into hydrogen fuel using a 1 MW PEM (polymer electrode membrane) electrolyser, which is then used to heat a school, power council vans, docked ferries and a mainland building [17]. Zhao et al. [18] conducted a cost cycle analysis of the Orkney scheme through a consideration of the entire hydrogen production, storage and distribution process. The study showed that although the scheme was successful in producing and utilising green hydrogen on the islands, analysis showed that the cost of hydrogen as a fuel is generally significantly higher than costs of current fossil fuel options. This was primarily due to electricity consumption during the generation process, which accounted for 71% of the £14.01/kg total cost of hydrogen production. This implies that although hydrogen production is technically feasible for renewable power systems, from an economic perspective, it should only be utilised during excess generation where the energy produced by the system would otherwise be wasted.

Overall, it is evident that there is limited research into the use of hydrogen specifically in distributed renewable power systems for remote islands, and that the area of research would benefit from more case studies to assess the feasibility of potential future implementation.

1.3. *Solar and wind*

Current existing renewable power systems use a combination of different generation technologies depending on the natural resources of the geographical area. Of the existing systems, PV solar panels and wind turbines are the most commonly used technologies due to their wide availability and the abundant natural resources of sunlight and wind often being prevalent - these benefits support the use of solar and wind, with worldwide reported annual growth rates for wind and solar PV of 21% and 55% respectively [19]. Solar and wind power are often used together in standalone renewable power systems due to the synergistic effect they often exhibit; each form of renewable generation makes up for the shortcomings of the other during their peaks and troughs of generation due to varying natural resource availability. This variation arises from wind speed change throughout the day and year producing intermittency in wind turbine output and varying solar radiation and cloud size distribution being the origin of intermittency for solar PV power output [20]. Aberilla et al. [9] noted this synergistic effect of wind turbine and solar power output due to their hourly generation profiles often complementing each other - up to a 70% reduced requirement for energy storage was reported from the case study. Badwawi et al. [21] conducted a review of hybrid solar PV and wind energy systems, identifying that additional capacity of PV panels and wind turbines in stand-alone systems are often a better choice compared to increasing battery storage, due to the high expense and relatively short lifespan of batteries.

It is evident that solar PV and wind turbines are an excellent method of renewable electricity generation with increased system reliability when used in combination with one another. These factors make them suitable and beneficial for integration into a distributed renewable power system.

1.4. *Isle of Rum – current system*

As mentioned earlier, the current system on the Isle of Rum is comprised of hydroelectric generators, a backup diesel generator and a battery storage system. The key issue is that there is only one form of renewable generation - if there is an issue or malfunction within the hydro system, there is no alternative renewable generation to rely on and fossil fuels would have to be utilised in the interim. There are limited reports assessing the current system on Rum, but some have indicated potential areas of improvement. Most recently, Dulas conducted a site assessment report on the Isle of Rum Hydro scheme in 2021 [22]. It identified several operational and safety issues with the hydro system, most notably due to an outdated intake pipeline and control system. Alternative layout options for the hydro scheme were presented, as well as immediate refurbishments, but a high capital cost was estimated - £750,000-£1million for a new scheme based on the existing layout and £2million for an alternative higher capacity (200 kW) scheme. Econnect Ventures also conducted a study into the use of renewable power systems on Rum [23]. In addition to consumption investigation on the island, the feasibility of additional renewable generation to offset decreased hydro output in the summer was considered. The study established potential sites for both 20 kW PV arrays and 6 kW wind turbines to be a beneficial addition to the power system. It was concluded that an appropriate sized installation would provide more system reliability through generation supplement for times when the hydro system has decreased or zero output. These technical assessments provide good evidence and support for the need of a new distributed renewable power system on the Isle of Rum that alleviates the shortcomings of the current system.

1.5. *Summary*

Although many authors have investigated the application of distributed renewable power systems for remote islands, there is limited evidence to suggest systems achieving full renewable and net-zero carbon emissions. In addition to this, heating demand for the case study area is often overlooked in existing studies. It is therefore necessary to carry out further research to find a solution for these islands. This research project is to address the shortcomings of current distributed renewable power systems used in islands, using the Isle of Rum as a case study, aiming to find a sustainable and net-zero solution by utilising the renewable resources available together with using hydrogen as the energy carrier to meet the electricity and heating demand on the island.

2. Methodology

2.1. *Island consumption and resource investigation*

The selected case study - Isle of Rum is not connected to central energy infrastructure - either a national electricity grid or natural gas pipeline. Sufficient data were found from multiple sources [2,22–24].

Through research via technical reports and data supplied by the island technical advisor, sufficient data was gathered for daily electrical consumption on the island for a 5 year period, dating 13/02/2017 to 01/11/2022 [22], as well as daily electrical generation from the current power system over the same period. From this data, each entry was sorted by month and averaged by year to produce mean daily consumption for a 12-month period in preparation for later full system simulations. The current electricity generation mix was also analysed in the same manor to achieve a baseline to assess improvement upon the new power system design.

Due to heating energy consumption for the Isle of Rum being done on an individual property basis using a mix of solid fuels, oil or LPG [23], there was no available daily data for heating consumption. Therefore, for full and accurate simulations to take place, estimations of the heating demand were made. This was done by taking the total yearly heating consumption obtained from [23], and scaling this annual value to the current 2022 population from [1]. From this, national daily gas consumption from the Scottish Energy Statistics Hub [25] was averaged over the previous 10 years for accuracy and then each daily entry was normalised. Daily consumption estimations were then made by mapping the normalised entries over the new scaled total annual heating demand for the island.

To further discretise the energy demand data into an hourly profile, domestic hourly energy consumption data from [26] was analysed and normalised to project onto the obtained daily consumption data for the Isle of Rum. The hourly load profile obtained is observed in Fig. 1 - this graph displays a normalised scale based on total daily energy consumption, the data plotted shows the hourly demand fluctuation, as well as the variation across the month investigated. In doing this, system simulations could be more accurate by appropriately meeting the predicted hourly fluctuations in energy demand throughout each day for the simulated year.

A thorough investigation into the natural resources in the island area had to be taken to establish which forms of renewable energy would be most suitable to meet the power demand. The resources investigated were that of wind, solar and tidal. Using online weather databases [27], hourly averages were obtained for sunlight, solar radiation, wind speed and wind gusts - it was decided that tidal power would not be as beneficial to the power system given the lower potential for power generation in this geographical location. Shown in Fig. 2 are the monthly averages of the wind speed and solar irradiance, obtained from the hourly data analysed.

Wind speed was fairly constant throughout the year, with some decline notable in the summer months. Solar irradiance, as expected, was much greater in the summer months due to more hours of sunlight per day. The designed system incorporated solar panels due to this reason, the decreased power output from the wind turbines in the summer months are supported by that of the solar panels thereby ensuring a reliable supply year-round.

2.2. *Power system modelling*

The design of a new power system for the island involved power generation from multiple renewable energy sources, starting with the existing system as a baseline. These sources included hydroelectric (based on the historic generation from the current system [24]), wind and solar.

To simulate the power generated from wind turbines using the wind speed data gathered, Eq. (1) was used;

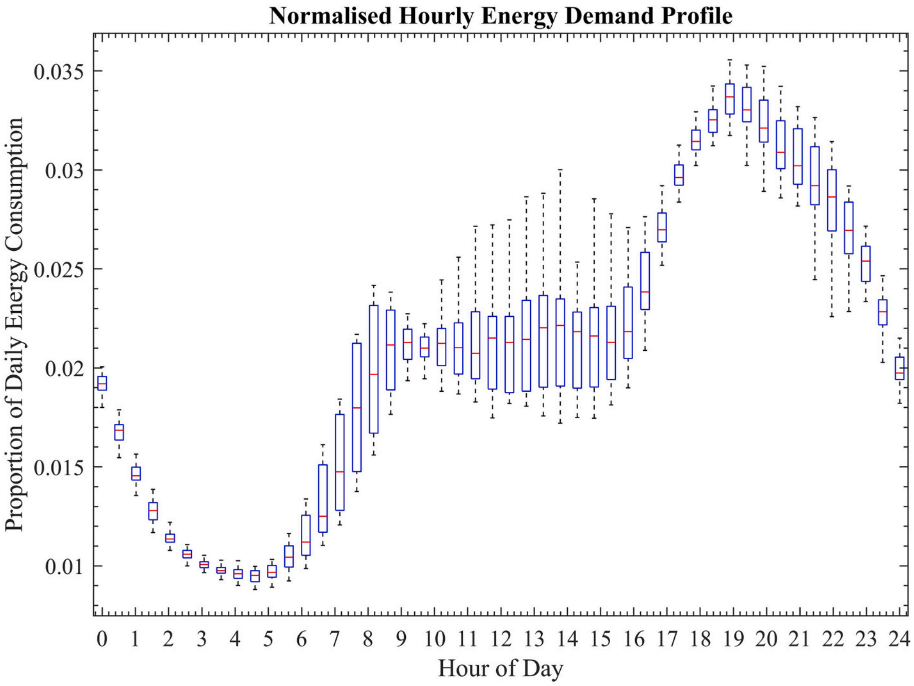


Fig. 1. Hourly energy demand profile - based on statistics from [26], used to project onto daily electrical and heating consumption data for the island.

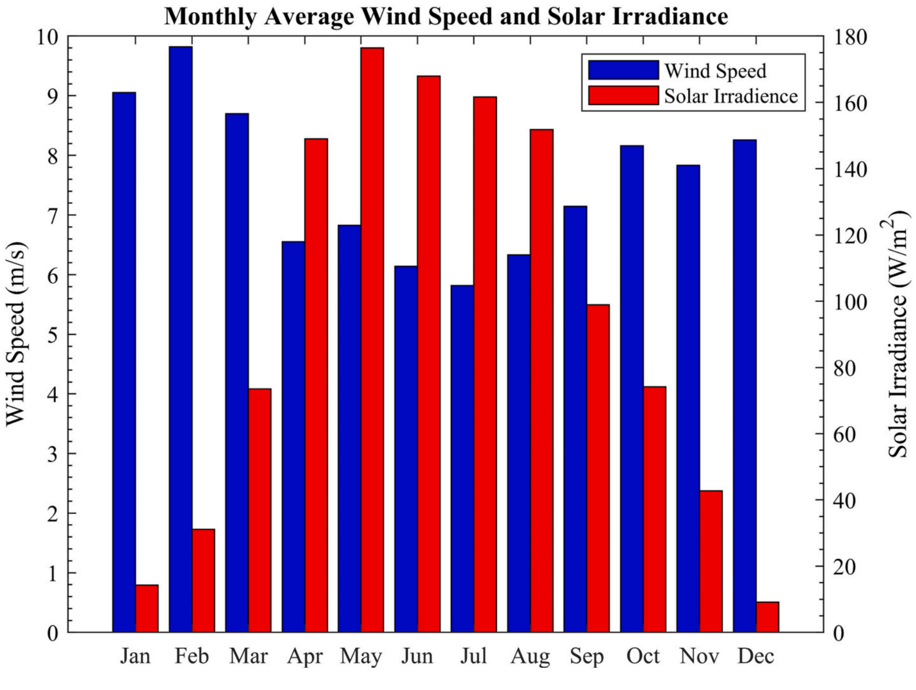


Fig. 2. Monthly average wind speed and solar irradiance of the Isle of Rum. Data sourced from [25].

$$P = \frac{1}{2}\rho A v^3 C_p \tag{1}$$

where P is the output power of the wind turbine (W), ρ is the air density (kg/m^3), A is the rotor swept area (m^2), v is the wind speed (m/s) and C_p is the power coefficient.

The power coefficient, C_p, is unique for different wind turbines and is defined as the ratio of extracted power from the turbine to the total available power in the wind source [28]. According to the Betz limit [29], the power coefficient of a wind turbine can not exceed 0.593, due to a function of tip speed ratio and collective blade pitch angle. Additional factors contributing to the overall turbine efficiency are that of generator efficiency, gearbox efficiency and capacity factor [30]. The power coefficient and overall turbine efficiency varies with wind speed and in order to simulate this, the power curve obtained from the turbine technical data sheet, [31], was used to create an equation for the turbine efficiency by using an iterative procedure to match the manufacture supplied power curve. The model achieved produced an averaged error margin of 1.2% when compared with manufacture supplied power output data for set wind speed points. In doing this, the output power for each 6 kW turbine used could then be modelled in the power system design for the island, taking into account losses over a variable wind speed.

The power output modelling of the solar panels used in the simulations was based upon REC TwinPeak 4 module parameters [32]. A baseline ideal efficiency of 19.7% was utilised to model peak output efficiency of the solar panels in respect to the incident solar radiance. Solar panels are also affected by cell temperature and low light behaviour; to account for this, Eq. (2) calculated the cell temperature of the panel for a given air temperature:

$$T_{cell} = T_{air} + \frac{NOCT - 20}{80} S \tag{2}$$

where T_{cell} is the cell temperature, Tair is the air temperature, NOCT is the nominal cell operating temperature, S is the irradiance in mW/cm^2 [33]. Using eq. 2 along with a temperature power coefficient of $-0.34\%/°C$, and hourly temperature data [27], the model took into account the effect of current air temperature on power output. To model losses from low light behaviour, the typical low irradiance performance characteristic of the module was utilised from the data-sheet and extrapolated for irradiance below 100 W/m^2 [32].

With these equations, along with the existing power supply data from the hydroelectric generators in place on the island, system modelling was able to be set up and conducted to meet generation requirements for the energy demands.

2.3. Energy storage modelling

For system modelling to ensure reliable supply during periods of low renewable generation, energy storage technologies were utilised. For the simulation cases that utilised batteries for energy storage, the existing battery system on the Isle of Rum was used to base modelling from - that is 12 × 15.36kWh Lithium Iron Phosphate (LFP) battery modules [34] and 9 × 6 kW bidirectional battery inverters [35], giving a total maximum battery storage capacity to 184kWh. To avoid overcharging and deep discharging of the lithium-ion batteries (improving battery health and longevity), simulations assumed state of charge (SOC) operating limits of 20–80% of maximum capacity [36]. Battery charge and discharge rates are based on the current used; the current, and hence maximal charge/discharge rates of the batteries were determined by the rated current of the inverter - 115 A charging and 136 A discharging. By using battery parameters from [34], a MATLAB Simulink battery module was used to obtain a characteristic discharge curve and thereby determine the rate at which the battery system could be charged/discharged in accordance with the hourly Excel data.

For cases that used hydrogen systems, modelling was based on the NEL H4 electrolyser [37], and a modified diesel gen-set based on the current 60kVA gen-set used on the island. The electrolyser was selected by ensuring the maximal period of hourly excess generation of each system could be used completely to generate hydrogen - the 28kWh maximal capacity of the electrolyser ensured this. The modification of the gen-set was based on a study by Gomes et al. [38]. From experimental setup it was found that a diesel engine can be modified successfully for hydrogen direct injection, achieving up to 50% greater efficiency compared to diesel. For this project, the modified gen-set was assumed to have the same efficiency for both hydrogen and diesel operation modes to account for the limited research available on the subject. The 60kVA diesel generator currently installed on the island (FG Wilson P50—5S) was used for system modelling, using a fuel consumption rate of 14.1 l/h for a 100% load operation of 48 kW [39], along with the LHV value of diesel to calculate the generator efficiency to be 33.46%. This efficiency value along with the LHV value of hydrogen was then used to calculate the corresponding hydrogen consumption rate for the modified generator. Table 1 summarises the results that were obtained and used to model the hydrogen/diesel gen-set in the system simulations.

Table 1
Gen-set fuel comparison.

Fuel	LHV (MJ/kg)	Generator Efficiency	Energy Output (kWh/kg)
Diesel	42.6	33.46%	3.958
Hydrogen	120.0	33.46%	11.142

2.4. Power system design iterations

Several different cases were considered to find an optimal power system design to fulfill the island demand. A total of 6 cases were considered, with cases 1 to 4 fulfilling the electrical demand of the island, and cases 5 and 6 fulfilling the domestic and total heating demands respectively (in addition to the electrical demand).

Case 1, the current island system, shown in Fig. 3, was used as a baseline to compare the improvement of the other designs to. Case 2 involved 5x6kW additional wind turbines and 60x350Wp solar panels to supplement the current island system, as shown in Fig. 4 (a). Case 3, depicted in Fig. 4 (b), used the same generation technologies as Case 2, but with a hydrogen energy storage system to supplement the existing battery system on the island. Case 4, shown in Fig. 4 (c), involved the hydrogen energy storage system completely replacing the current battery storage system. Finally, Case 5 and 6, shown in Fig. 4 (d) and (e), investigated the heating demand as well as the electrical demand on the island, through the use of larger capacity wind turbines and heat pumps to meet the domestic and total heating demand respectively.

Cases 2, 3 and 4 only simulated the electrical load of the island so that a direct comparison to the current system, Case 1, could be drawn as the current system only supplies electrical power. Cases 5 and 6 are separate cases that theoretically could meet the heating demand as well, but may not be directly compared to the other cases from a technical and economic standpoint, due to the difference in demand requirements.

2.5. Techno-economic analysis

The results of the system simulations needed to be compared from both a technical and economic perspective. From a technical perspective each system's ability to reliably meet the energy demand through renewable sources was assessed by comparing the generation splits and predicted amount of diesel used over the course of 1 year for the Isle of Rum. From an economic perspective, a 20-year cost analysis was conducted for each case considered, by taking into account the capital expenditure (CAPEX), predicted operation and maintenance costs (OPEX) and typical life cycle of each system component, along with the associated replacement cost. From the 20-year cost analysis, for each case, the total life cycle cost (TLCC) was calculated, along with the levelised cost of energy (LCOE) to compare against each case.

3. Results and discussion

3.1. Consumption and resource baselines

Utilising the data collection and analysis methods from section 2, the current daily electricity consumption of the island is shown in Fig. 5. The data has been categorised by month, showing the averages and ranges for daily electrical consumption.

As shown from Fig. 5, the current electricity demand of the island is relatively constant throughout the year, averaging 400KWh/day, with a decrease during the summer months. This is because daytime in the summer is long and warm, less electricity needed for lighting and other electrical appliances. The results of the daily heating demand estimates are shown in Fig. 6, categorised by month - averaging 2.41MWh/day. It is evident from Fig. 6 that the daily demand is much higher in the winter due to the decreased outdoor temperature; and the heating demand is lower in the summer because the outdoor temperature is warm, so no heating is needed. This seasonal variation in demand illustrates the

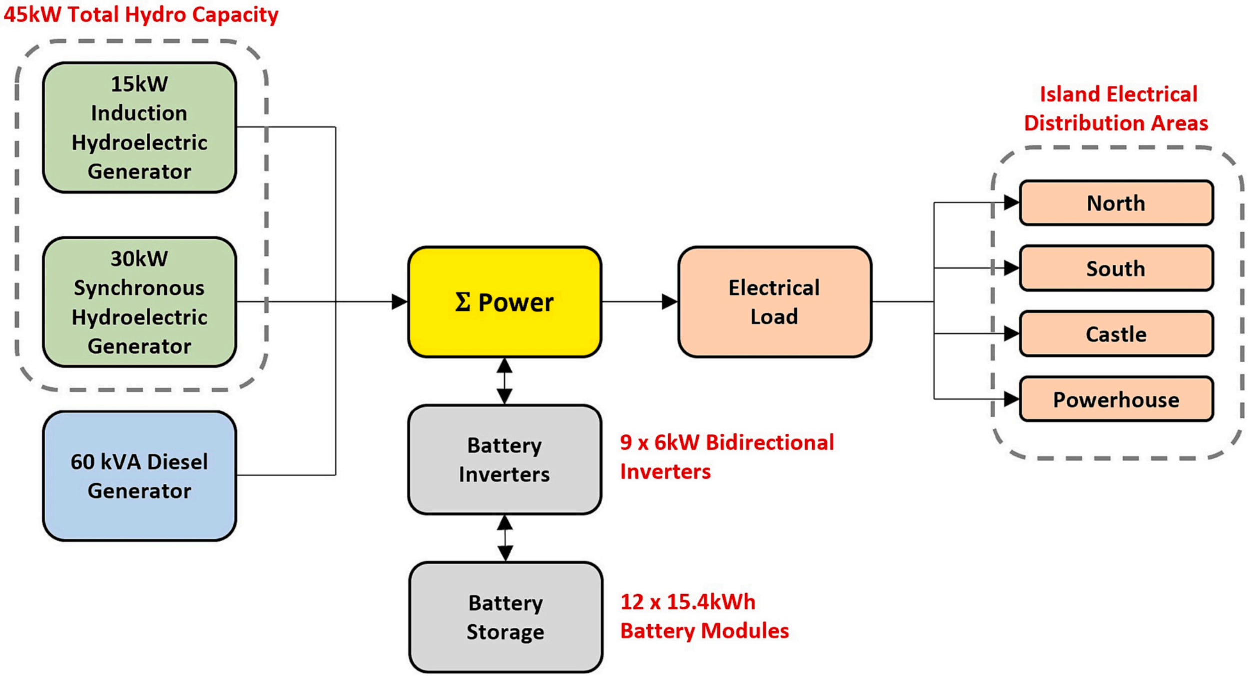


Fig. 3. Case 1 simplified schematic: existing island power system.

requirement for energy storage systems to supplement the renewable generation technologies present in the island power system, ensuring reliability.

3.2. System simulation technical results

For the 6 aforementioned power system design cases, hourly simulations were run for an averaged year to meet the electrical (Cases 1–6) and heating demand (Case 5 and 6 only) of the Isle of Rum outlined in Figs. 5 and 6. The key technical results outlining the performance of the first 4 systems (electrical load only) are outlined in Table 2, displaying the total yearly generation from each technology used, along with the calculated annual diesel consumption. It is worth noting that the sum of the yearly energy generation for each case is not the same. This is due to surplus generation throughout the year used to charge the battery system and/or generate hydrogen as a back-up fuel.

It is evident from Table 2 that Case 1, the current island system, performed the worst from an environmental perspective due to the amount of diesel consumed to meet the electrical demand. The total yearly diesel fuel consumption by the island generator was found to be 21,635.83 kg, which accounted for 58.39% of the total annual electrical energy generation on the island. This significant reliance on diesel fuel to meet the island's electrical demand supports the need for an improved system on the Isle of Rum.

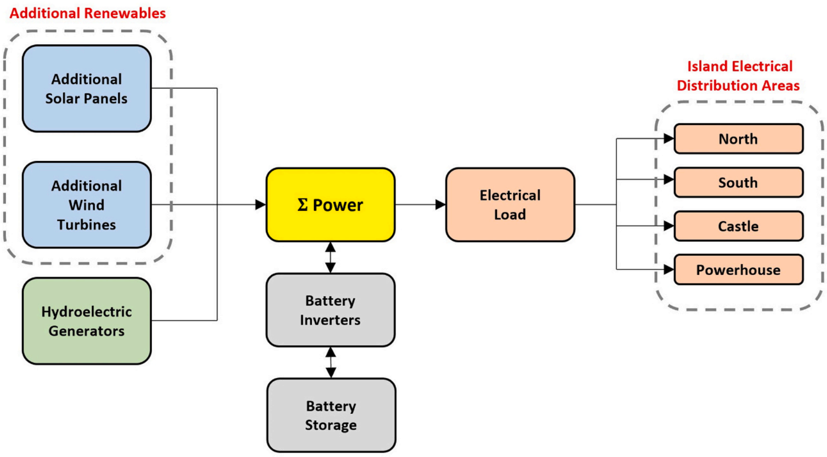
Case 2 significantly improved upon the baseline set from Case 1 - a 96.2% reduction in annual diesel consumption was observed when compared to that of Case 1 for meeting the electrical demand. From Table 2, it is shown that this amounted to 802.95 kg of diesel fuel consumed annually by the back-up generator. This significant reduction in diesel usage, and hence CO2 emissions, was primarily due to the utilisation of wind power - the 5 additional wind turbines in the system accounted for 56.45% of the annual energy generation from the simulations, proving to be the most impactful addition to the power system. The additional solar power only accounted for 8.5% of annual power generation, but was still a necessary addition to reduce overall diesel consumption due to the heightened power generation in the summer months supplementing the decrease in wind power generation, (from Fig. 2). Fig. 7 shows this clearly, displaying the monthly total generation split throughout the simulated year for the Case 2 system, compared to the total monthly electrical demand.

Fig. 7 illustrates that from April to July, the heightened generation from the solar panels makes up for the difference to the demand caused by the decreased generation from the wind turbines. Fig. 7 also shows the total monthly generation supply exceeding the demand in all months - it is worth noting that the diesel generator was still utilised due to select days when renewable generation was particularly low and battery storage was discharged to the full 20% limit. One of these worst case days was June 1st, the hourly generation profile against demand and battery SOC is displayed in Fig. 8.

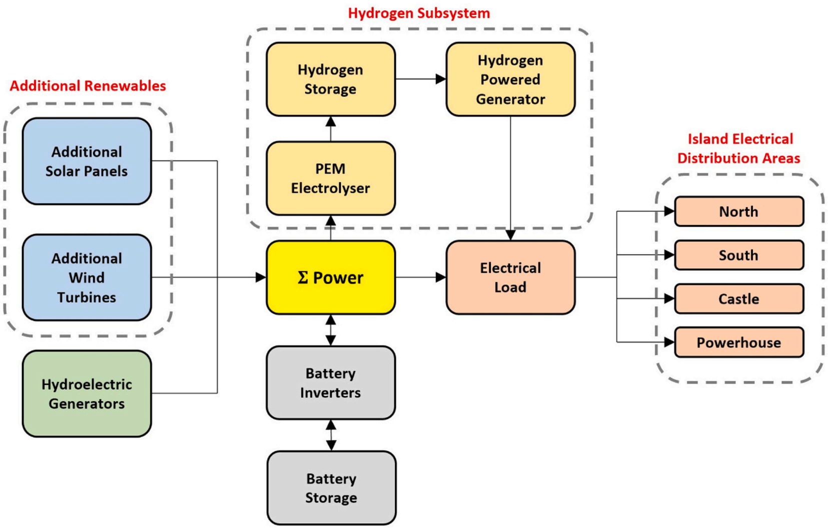
It is clear from Fig. 8 that the diesel generator makes up a significant proportion of the daily generation on June 1st of the Case 2 simulation. This worst case is present due the lower than average wind energy output caused by low wind speeds, particularly in the late hours of the day, accompanied by zero solar output due to no sunlight being present at night. As the battery system was already at its 20% SOC due to previous days of discharging as a result of low renewable availability, there was no energy available from the battery system to supplement the generation mix, hence the diesel generator was used. It is evident from this scenario that improving the energy storage of the power system would decrease diesel consumption particularly in days with high demand and low renewable availability, such as that presented in Fig. 8.

Referring to Table 2, the Case 3 simulation exhibited a drastic improvement by achieving a fully renewable generation split with zero diesel generator usage to meet the annual electrical demand. This was due to the additional energy storage provided by the hydrogen subsystem. Hydrogen was generated by the electrolyser in hours where the combined renewable energy supply exceeded the demand and the battery system was also already at its maximal SOC limit of 80%. It was found that a 120 kg compressed hydrogen storage was sufficient to supplement the battery storage system year round. By observing the same worst case scenario day as for Case 2, it is shown that the addition of the hydrogen subsystem supplements the battery storage to eliminate the requirement for diesel, depicted in Fig. 9.

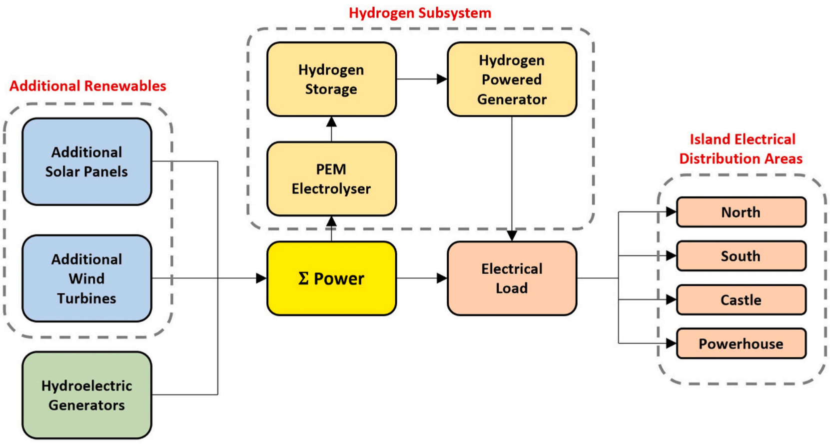
Highlighted from Fig. 9, for the worst case day of June 1st, in the latter hours where diesel was previously required in Case 2, for Case 3 where the renewable generation was not enough to satisfy the electrical



(a) Case 2 Simplified Schematic: Additional solar panels and wind turbines.

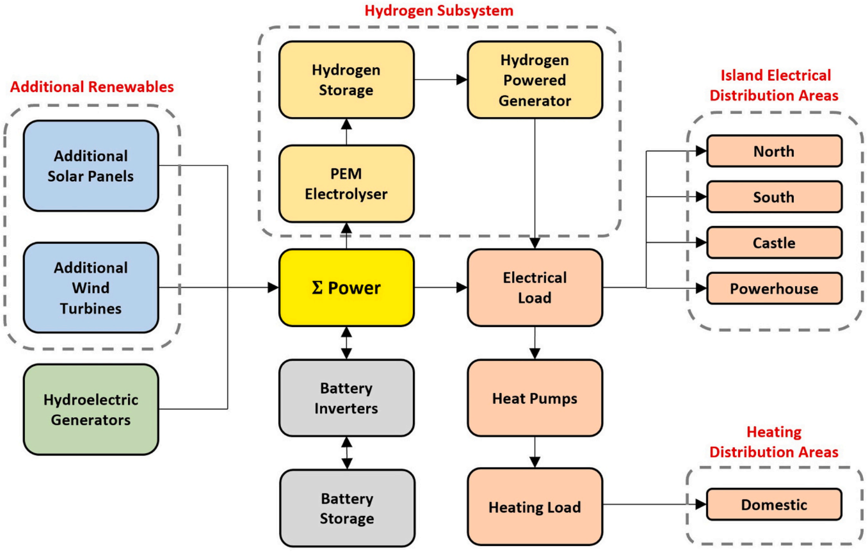


(b) Case 3 Simplified Schematic: Additional renewable generation with hydrogen generation and storage to supplement existing battery system.

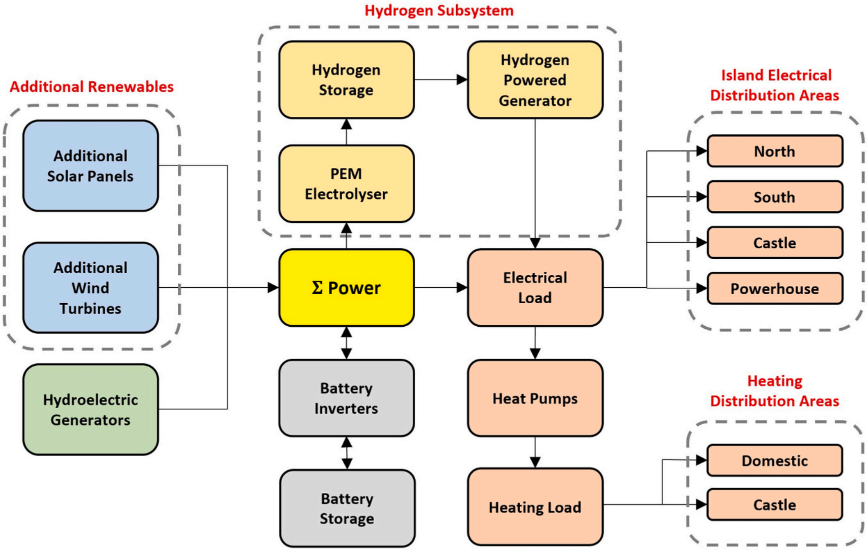


(c) Case 4 Simplified Schematic: Additional renewable generation with hydrogen generation and storage to replace existing battery system.

Fig. 4. Schematic designs of energy systems for the island.



(d) Case 5 Simplified Schematic: Domestic heating demand included in system.



(e) Case 6 Simplified Schematic: Total heating demand included in system.

Fig. 4. (*continued*).

demand, and the battery was at its lower limit, the level of hydrogen storage was decreased from 58% to 51% of the maximal 120 kg to supply the modified generator with hydrogen fuel to make up the supply difference to the demand. The hydrogen storage level was already relatively high for this day due to previous weeks having excess renewable generation that was used to power the electrolyser and hence produce more hydrogen as a reserve fuel in case of days such as June 1st.

Fig. 10 shows the hydrogen storage level for Case 3 (blue line in the figure) and 4 (red line in the figure) over the simulated year, revealing a noticeable seasonal variation. During winter months, renewable hydrogen generation and storage reached its peak because more wind energy was available (as seen in Fig. 7), resulting in greater utilisation of excess electricity to produce hydrogen by electrolysis, thus increasing the % storage level in both Case 3 and 4. Conversely, in summer months, stored hydrogen was used to supplement the lower output from renewable energy sources, thereby decreasing the % level of hydrogen stored. The minimum hydrogen storage level happened for both cases in July, as low as around 2% (Case 3) and 10% (Case 4), as seen in the figure.

The final electrical only simulation was Case 4 which, as mentioned in the prior section, consisted of the same as Case 3, but fully replacing the battery storage system with the hydrogen subsystem. In order to meet the demand, this meant increasing the amount of 6 kW wind turbines from 5 to 7, as the hydrogen system had a lower round trip efficiency compared to the battery system. From Table 2 it is shown that Case 4 met the electrical demand with zero diesel fuel usage, this infers that Case 4 is a fully self-sufficient renewable power system as all system components produce renewable forms of energy without the utilisation of diesel fuel or battery storage. The simulation achieved this through a 40% increase in energy output from wind resources in comparison to Case 3 in order to produce more hydrogen in periods of excess wind resource. The maximum hydrogen storage used in Case 4 was also 120 kg, with the annual variation following a similar trend to Case 3, as seen in Fig. 10. The larger magnitude of the hydrogen storage level

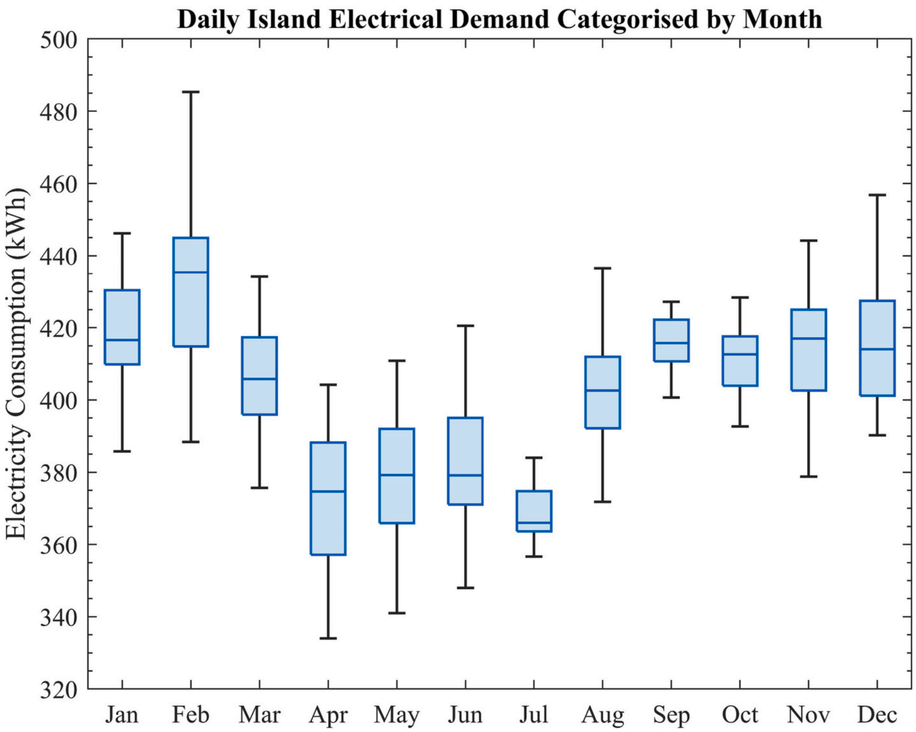


Fig. 5. Isle of Rum daily electricity consumption - the data has been averaged to a mean daily consumption, categorised by month.

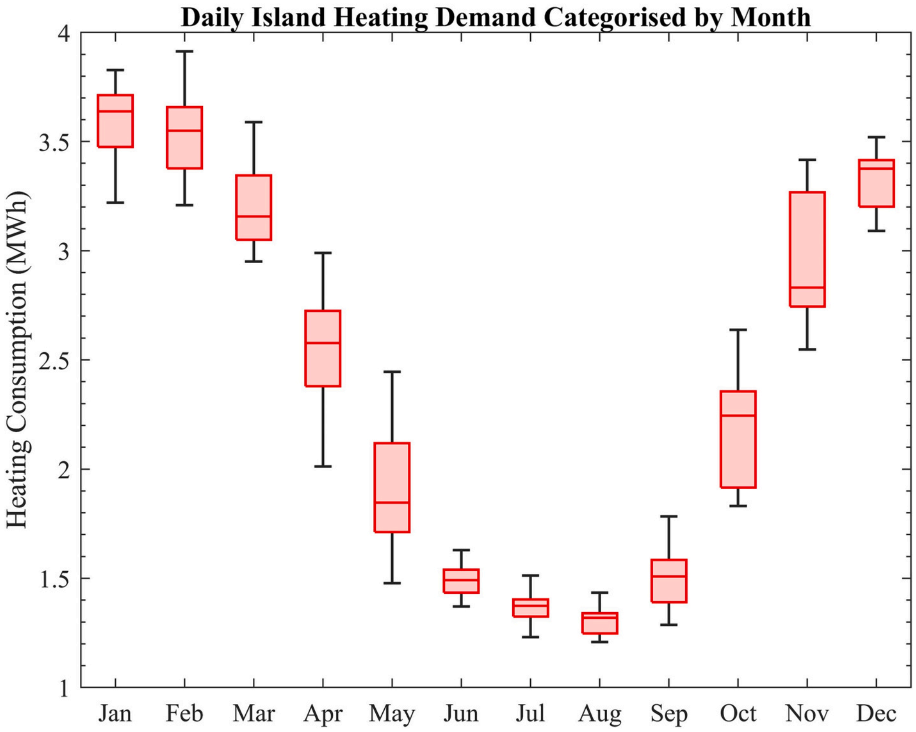


Fig. 6. Isle of Rum daily heating demand - the data has been estimated using statistics from [23,25], categorised by month.

throughout the year observed in Case 4 is due to the additional wind turbines providing more excess energy during periods of high wind speeds.

Finally, the Case 5 and 6 simulation results are presented in Table 3. It is important to note that Case 6 exhibits a larger yearly generation than Case 5 as it is designed to meet the full heating (and electrical) demand, as opposed to Case 5 which is designed to only meet the domestic heating (and full electrical) demand, and hence requires more energy generation. As mentioned earlier, for the heating demand, heat pumps were used in the simulations with an assumed coefficient of performance (COP) of 3.0 [40]. It was found that to fully meet the demands set for each case without use of diesel, larger wind turbines were required due to the heating demand being much larger than the electrical demand. For Case 5 this involved 1 × 60 kW wind turbine and 60 x

Table 2
System simulation results (electrical demand only).

		Case 1	Case 2	Case 3	Case 4
Total Yearly Generation (kWh)	Hydro	61,020.77	61,020.77	61,020.77	61,020.77
	Wind	–	103,311.25	103,311.25	144,635.75
	Solar	–	15,502.93	15,502.93	15,502.93
	Diesel	85,644.40	3178.44	0	0
Annual Diesel Fuel Consumption (kg)		21,635.83	802.95	0	0

350Wp solar panels and for Case 6 this involved 2 × 60 kw and 1× 6 kW wind turbines and 90 × 350 Wp solar panels. Both cases also utilised the full existing island system and the same hydrogen subsystem mentioned in the previous cases acting as an energy storage medium.

It is seen that Case 6 had a much larger annual energy generation compared to Case 5, this is because 53.9% of the heating demand was from the large castle on the island, which Case 5 did not consider, skewing the results. However, both simulations concluded that with the described system setup, no diesel was consumed to meet the energy demands. The most common fuel currently used to meet the heating demand on the island is LPG [21], which has a LHV of 46.05 MJ/kg. Using this along with an average boiler efficiency of 90%, it was calculated that for the heating demand from Case 5 (excluding castle heating), an annual requirement of 28,201 kg of LPG would be needed to meet this. Using the same methodology, for the Case 6 demand (total island heating), 76,155 kg of LPG would be required. With both Case 5 and 6 simulations achieving zero fossil fuel usage to meet their respective energy demands, this shows a drastic environmental improvement when compared to the island at present.

3.3. Economic analysis

Table 4 summarises the results of the 20 year cost analysis conducted. It was found that the life cycle of the hydroelectric generator, wind turbines, solar panels, electrolyser and generators used were all at least 20 years, hence there is no replacement cost for these over the analysis period. The only replacement costs are that of the battery modules used, which have a life cycle of 10 years [34]. Current prices for models of wind turbines [31], solar panels [32], battery modules [34] and generators [38,39] used were obtained from manufacturers and used in the CAPEX costs of the analysis. Due to the limited knowledge and availability of the technology, CAPEX for the hydrogen subsystem was estimated based on current cost projection studies [41,42]. OPEX costs used were based on a fixed rate according to the technology used, varying from 2 to 17% of initial CAPEX for an annual expenditure [43].

Table 4 shows that Case 1 (current island system) has a CAPEX of zero - this is because no new components are purchased. CAPEX costs increase with the amount of components used in each system - it is shown that Case 3 and 4 have a significantly higher CAPEX than Case 2, this is due to the high cost of installation of the hydrogen subsystem, which Case 2 does not incorporate. Case 5 and 6 in particular have a much larger CAPEX due to the significant heating demand on the island, requiring more renewable generation technology, in addition to heat pump installation. Despite the low CAPEX of Case 1, Table 4 indicates the TLCC of Case 1 is the highest of the electrical only systems - this is due to its significant use of diesel fuel, meaning that over the 20 year analysis, the cost of the fuel contributed significantly to the £776,210.08 OPEX. The TLCC of Case 2 is the lowest of all systems, this is again because there is no hydrogen subsystem included, meaning CAPEX and OPEX of the elctrolyser and compressed hydrogen storage was not applicable. This is evident from the 66% increase in TLCC from Case 2 to Case 3, where the only system difference was the inclusion of the hydrogen subsystem. However, the TLCC of Case 4 is 13% lower than that of Case 3 - this was due to the battery system having a larger OPEX over the 20 year period than the hydrogen subsystem, as the batteries needed to replaced every 10 years. From this it can be concluded that hydrogen generation and storage can be an economically viable standalone clean energy storage medium for island power systems.

Observing the LCOE from Table 4, the same trend is observed as for the TLCC for the first 4 cases, as all 4 systems meet the same electrical load. However, it is shown that Case 5 and 6 exhibit the lowest LCOE of all cases by a significant margin. This can be explained due to the fact that both cases utilise heat pumps to meet the heating demands of the island, which have a very high efficiency (COP of 3.0). This skews the

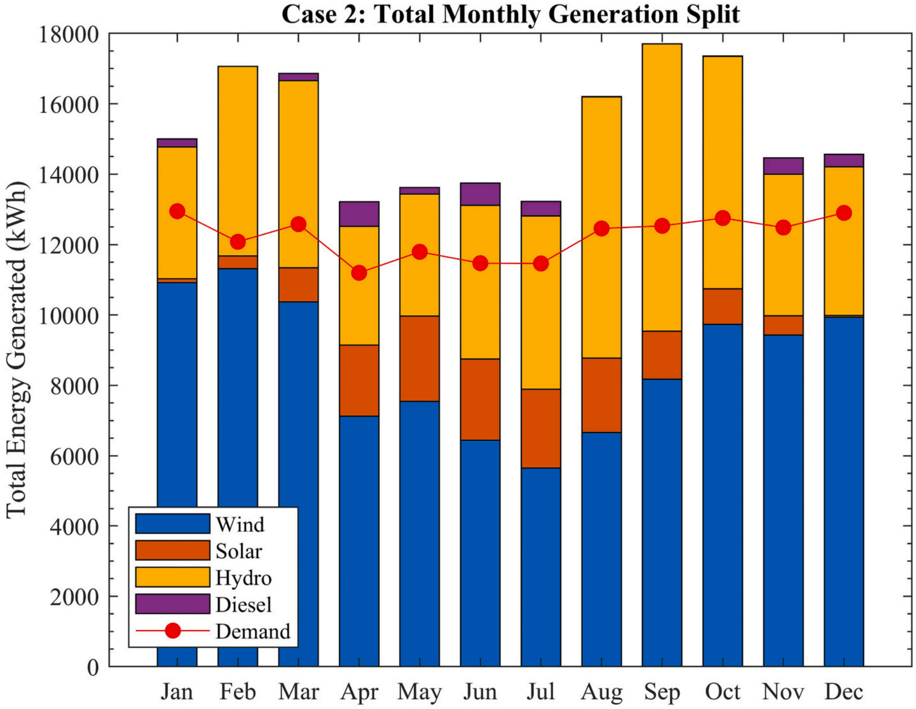


Fig. 7. Case 2 simulation results - the monthly total of the different generation technologies utilised is compared to the monthly total electrical demand.

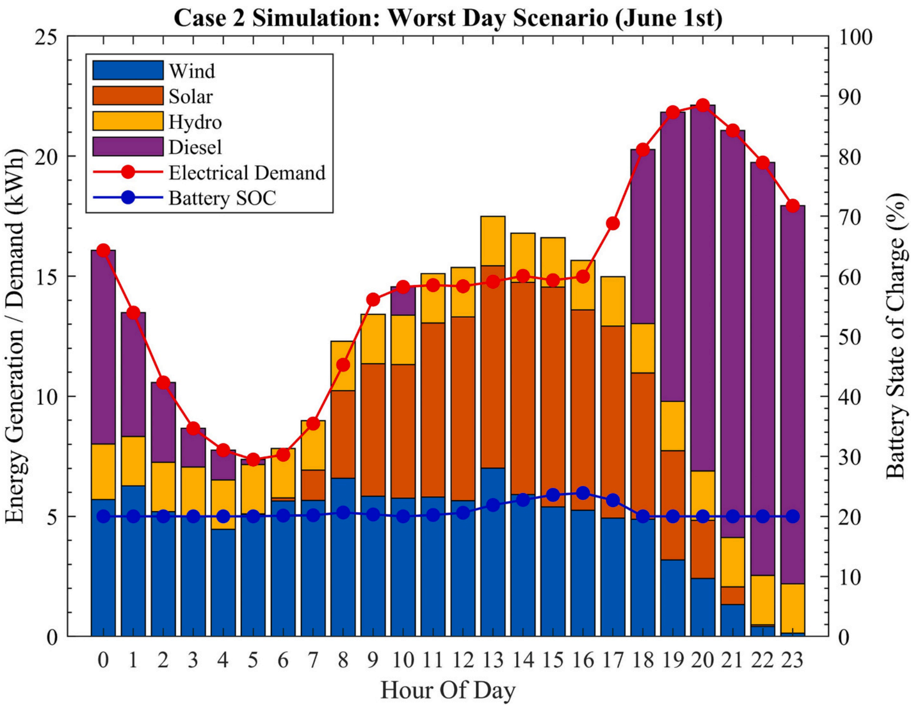


Fig. 8. Case 2 simulation results - worst case day scenario occurred on June 1st. There is a significant use of the diesel generator in the late hours.

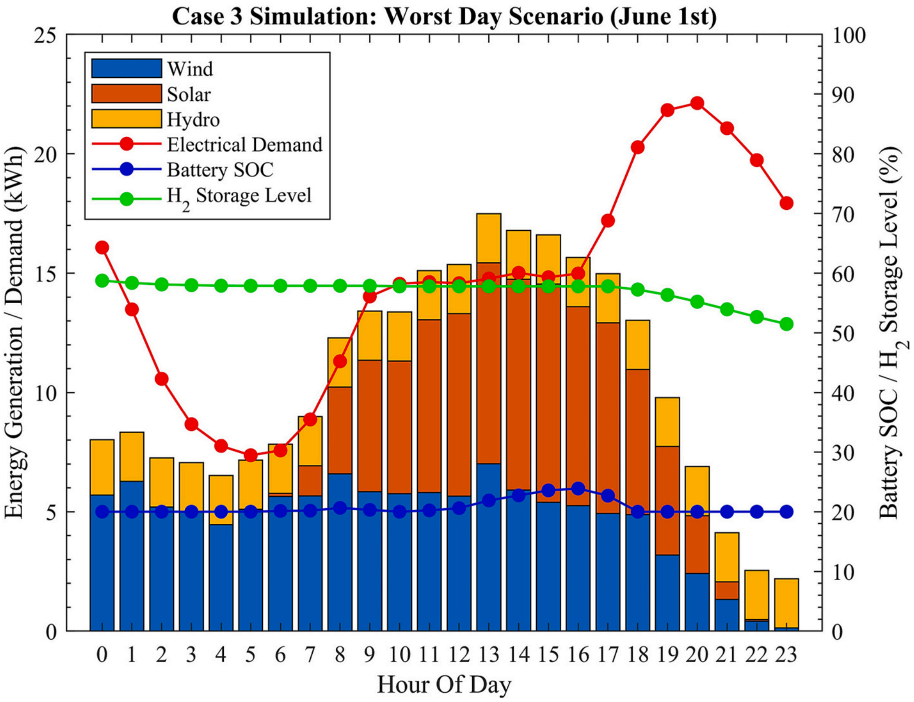


Fig. 9. Case 3 simulation results - worst case day scenario occurred on June 1st. The hydrogen powered generator is utilised where diesel was required previously in Case 2, shown by the decreasing % level of H_2 storage.

results for the LCOE of Case 5 and 6 when compared to other cases. Case 6 has a lower LCOE of £0.76/kWh compared to £1.86/kWh of Case 5, this is due to Case 6 meeting a heating demand that is 2.7 times larger than Case 5, from the inclusion of the large castle heating demand. Overall, this economic analysis has established that an improved renewable power system on the Isle of Rum would result in an overall cost reduction over a 20-year period. At current, prices of hydrogen technology remain high, but in the future as the field is developed further, prices may decrease and CAPEX for such systems may become more feasible.

4. Conclusions

From this study, it was found that:

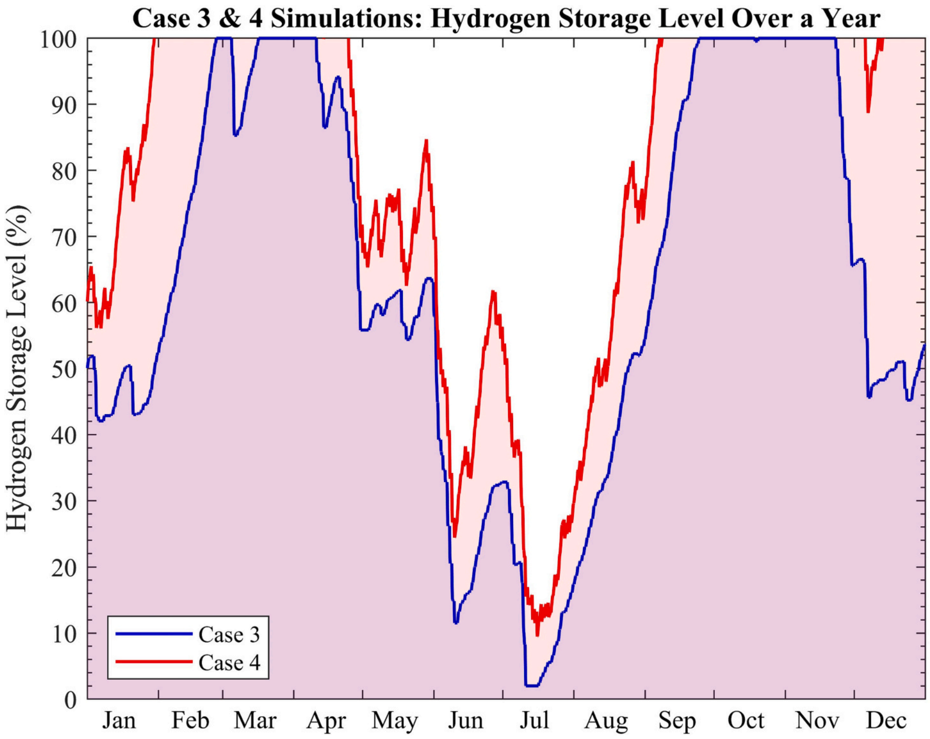


Fig. 10. Case 3/4 simulation hydrogen storage level - the hydrogen storage level is shown as a percentage of the maximal storage capacity of 120 kg.

Table 3
System simulation results (including heating demand).

		Case 5	Case 6
Total Yearly Generation (kWh)	Hydro	61,020.77	61,020.77
	Wind	266,832.63	554,327.50
	Solar	15,502.93	23,254.39
	Diesel	0	0

Table 4
Economic analysis results – 20-year cost analysis.

	CAPEX (£)	OPEX (£)	TLCC (£)	LCOE (£/kWh)
Case 1	0.00	776,210.08	776,210.08	5.29
Case 2	185,541.32	257,935.47	443,476.79	3.02
Case 3	312,891.32	423,777.00	736,668.32	5.02
Case 4	381,965.32	258,600.00	640,565.32	4.37
Case 5	427,461.12	449,577.00	877,038.12	1.86
Case 6	772,511.08	511,377.00	1,283,888.08	0.76

- The Isle of Rum's energy demands can be met with fully renewable resources, through the inclusion of a novel hydrogen generation and storage subsystem.
- With the inclusion of wind turbines and solar panels to the system, Case 2 exhibited a 96.2% reduction in diesel consumption.
- Both Case 3 and 4 achieved a fully renewable generation mix through the addition of a hydrogen subsystem comprised of a 28 kW PEM electrolyser, 120 kg compressed storage and modified gen-set. Case 4 achieved this with only the hydrogen system as its energy storage medium, whereas Case 3 was supplemented with the current 184kWh battery system in place on the island – this meant Case 4 required 12 kW extra wind turbine capacity due to the round-trip efficiency of the hydrogen system being lower than that of the battery.
- Both Case 5 and 6 also achieved a fully renewable generation mix, meeting the domestic heating and full heating island demands respectively through the integration of heat pumps. For these two systems, this meant using a total wind turbine capacity 60 kW and 126 kW respectively, in addition to 60 and 90350Wp solar panels, integrated with the current island system and new hydrogen subsystem.
- Assuming that the lifetime of the system is 20 year, economic analysis concluded that Case 2 exhibited the lowest cost, with a LCOE of £3.02/kWh, a 43% reduction from Case 1. Both Case 3 and Case 4 also had a lower LCOE than Case 1 of £5.02/kWh and £4.37/kWh respectively. This shows that the hydrogen subsystem designed can be an economically viable option despite its currently high CAPEX. Both Case 5 and 6 had the highest CAPEX of all systems, due to the additional generation technology required to meet the additional heating demand. However, they achieved the lowest LCOE at £1.86/kWh and £0.76/kWh, due to the high efficiency exhibited by the heat pumps used for the heating load.
- Further research may build upon these findings by investigating the use of combined heat and power generation in the island's system, through the wasted heat recovery of the hydrogen powered generator to supplement the heating demand. Additionally, the possibility of utilising excess hydrogen produced in such a system as fuel for transportation, either on the island or to and from the island via boat, could be investigated as the relevant technology advances.

CRediT authorship contribution statement

Luke Williams: Writing – original draft, Software, Methodology, Investigation. **Yaodong Wang:** Supervision, Conceptualization.

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

The authors are unable or have chosen not to specify which data has been used.

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