Received: 8 March 2023 | Revised: 26 June 2023 | Accepted: 28 June 2023
IET Energy Systems Integration
DOI: 10.1049/esi2.12108

ORIGINAL RESEARCH

Sizing, economic, and reliability analysis of photovoltaics and energy storage for an off-grid power system in Jordan

William Seward[1] | **Lixun Chi**[2] | **Meysam Qadrdan**[1] | **Adib Allahham**[3] | **Khaled Alawasa**[4]

[1]Cardiff University, Cardiff, UK
[2]PetroChina Planning and Engineering Institute, Beijing, China
[3]Northumbria University, London, UK
[4]Mutah University, Karak, Jordan

Correspondence
William Seward.
Email: sewardwg@cardiff.ac.uk

Funding information
Royal Academy of Engineering, Grant/Award Number: TSP2021\100334

Abstract
Remote areas in Jordan often rely on expensive and polluting diesel generators to meet their electricity demand. This study investigates 100% renewable solutions to supply the electricity demand of off-grid energy systems through optimal sizing of photovoltaics and energy storage systems. A linear programming approach is proposed to minimise the annualised cost of electricity supply including capital costs of equipment and their operation and maintenance costs. The optimisation determines the size of photovoltaics and energy storage required to satisfy electricity demand at every hour of a selected year. A Jordan campsite was used as a case study to assess and compare the performance of PV-battery storage and PV-hydrogen storage systems from economic and reliability perspectives. The results show that hydrogen storage was more economical for a 100% renewable energy system. However, introducing some diesel generation gave the battery system a significantly lower annualised cost of energy.

KEYWORDS
battery storage plants, distributed power generation, hybrid power systems, photovoltaic power systems, reliability

1 | INTRODUCTION

Diesel generators are the most common source of electricity generation in off-grid areas of Jordan. The inability to connect demands in remote areas to the main electricity network is due to several environmental and geographic challenges. One such challenge is the distance from the main electricity network to the remote demands, where the high capital cost of power line infrastructure is prohibitive. Another significant challenge is regulation limiting construction of new electricity infrastructure for reasons related to aesthetic and natural beauty. Thus far, these challenges have prevented electricity supply to remote demands that rely on expensive diesel generators.

Renewable generation technologies with energy storage are an alternative to existing, high cost diesel generators, with the potential to alleviate the cost of electricity for these remote areas. Many combinations of renewable generation and storage technologies have been proposed and discussed in literature. There is potential for integrated energy systems to play an important role in reducing the cost and greenhouse gas emissions from diesel generators in remote areas. A typical configuration uses a combination of renewable energy generation (wind, photovoltaics (PV), biomass), an energy storage system (battery, hydrogen storage), and small backup diesel generators. Jordan is blessed with an abundance of solar energy; Figure 1 shows the global horizontal irradiation map for Jordan, where the average annual sum has a range of 2100–2400 kWh/m2 [1].

Several research studies address the conversion of conventional off-grid energy systems to reduce their environmental impact. A feasibility study for a hybrid energy system in a remote community in Bangladesh was presented in ref. [2]. The study considered five technologies: diesel generators, PV panels, wind turbines, battery energy storage and inverters. The study concluded it was practically impossible to achieve equality with grid prices. In ref. [3], a PV and diesel generator

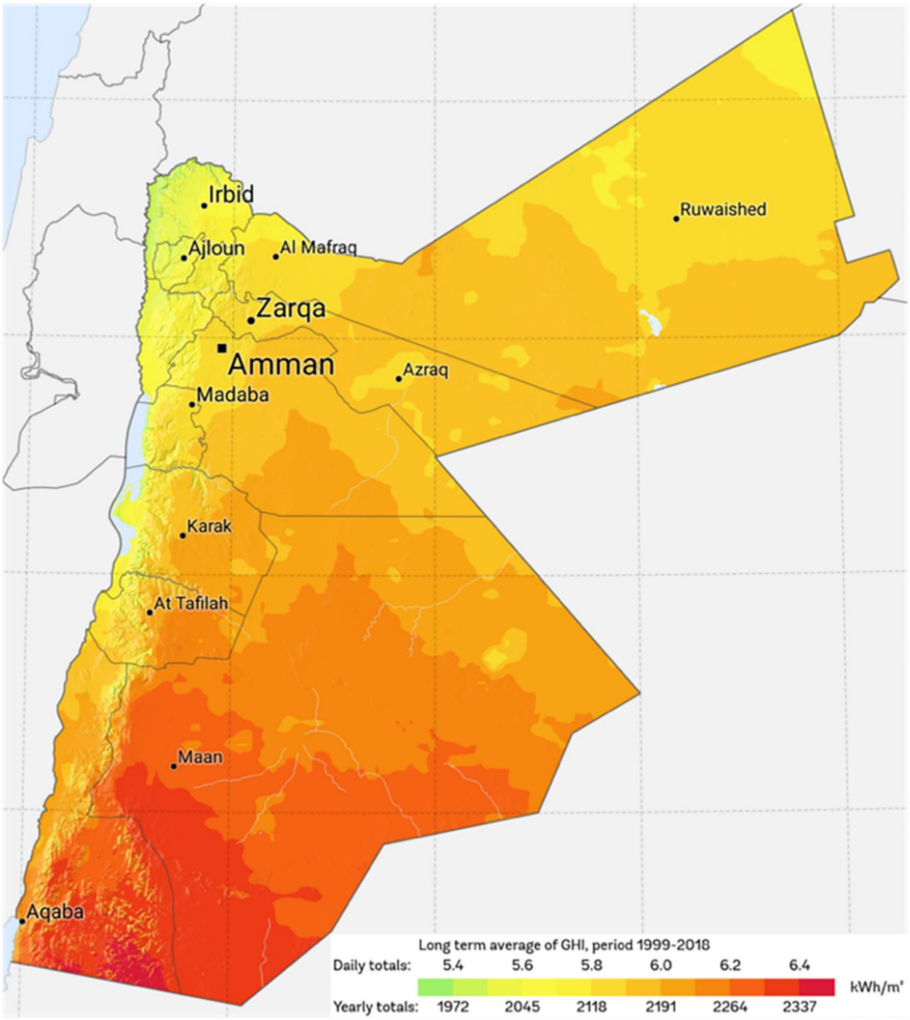

FIGURE 1 Solar map of Jordan, showing global horizontal irradiation [1].

system was studied for rural areas of Bangladesh. The study revealed that an optimal PV, diesel generator and battery system does not reduce overall energy cost. However, such a combination decreases the dependency on diesel generation and hence, reduces greenhouse gas emissions. In ref. [4], a feasibility study was performed for hybrid energy systems in five rural communities in Sub-Saharan Africa. The proposed systems consisted of five technologies: diesel generators, PV panels, wind turbines, hydropower and battery storage. The study showed that hybrid energy systems with combinations of these technologies are adequate solutions for energy supply at those rural communities. These studies demonstrate the feasibility of off-grid energy systems with diesel generators but highlight the challenge of being cost competitive with grid. Additionally, they still assume some diesel generation with greenhouse gas emissions.

A study of rural electrification for a community in India was presented in ref. [5]. The combination of small hydropower, PV panels, wind turbines, batteries, and a bio-diesel generator are compared to find an optimal off-grid electricity supply. The study compared the off-grid renewable energy system solution with a conventional grid extension. Conclusions of the study indicate the renewable energy solution can be a cost-effective alternative, with hydropower significantly reducing the cost and making the energy mix more attractive. Although this study achieves a cost competitive off-grid renewable energy system, without fossil fuel diesel generation, a significant contributor is hydropower. In Jordan, hydropower is not an option for decarbonising off-grid energy systems.

A hybrid energy system for an off-grid village in South Africa was studied in ref. [6]. Three scenarios were studied: a PV and battery storage system, a PV and diesel generator system, and a PV, battery and diesel generator system. The study showed that the first scenario (a PV and battery system) was the most reliable and cost-effective system. In ref. [7], a techno-economic study was carried out for an off-grid PV and battery system, for a remote area in Cameroon. The study indicated that with an optimal configuration, the demand can be satisfied for the entire year. However, a large PV array was necessary, which impacted the economics of the project. The design of an integrated energy system based on PV, battery and biomass was considering for a techno-economic and environmental study in ref. [8]. The study revealed that such a design can be applied in any remote area of developing countries. These studies consider scenarios with 100% renewable off-grid energy systems. They identify the versatility and applicability of renewable energy systems but highlight challenges related to the high cost of energy and the large area required for PV arrays.

Although these studies present positive results for off-grid renewable energy systems, they also highlight the challenges of presenting an attractive investment case and being cost competitive with conventional fossil fuel solutions. Additionally, these studies do not capture demand requirements and PV generation characteristic of the Jordanian off-grid tourist regions.

The work presented in ref. [9] investigated the performance of several algorithms to obtain the optimal size of an off-grid PV, biomass and battery system for a small remote village in Egypt. Among the algorithms was a modified quantum model of Runge Kutta algorithm which achieved the optimal solution for the proposed system. In ref. [10], a hybrid renewable energy system in Jordan was designed using HOMER Pro, an optimal renewable energy system design tool. On grid and off-grid energy systems were compared. The study shows a combination of wind, solar and battery operating with a connection to the grid resulted in environmental and reliability benefits. These studies address the sizing and design of renewable energy systems for off-grid applications but an adaptable methodology and specific conclusions that target off-grid rural areas in Jordan is required. Furthermore, accessibility to paid for programs such as HOMER limits the applicability of the design process in ref. [10]. Finally, a comparison of different energy storage technologies would contribute to a better understanding of possible solutions for prospective investors.

The authors in ref. [11] present analysis of a hybrid off-grid energy system consisting of PV panels and a battery storage system, in the Jordan Valley area. The study investigated the impact of temperature on the performance and efficiency of a PV and battery system. The results show that the temperature variation greatly impacts the efficiency of the PV system. Therefore, temperature impacts need to be considered in the design of PV systems for off-grid applications.

In Jordan, off-grid energy systems, such as tourist camps, remote villages and farms, are suffering from the high cost of conventional generation. The off-grid energy systems are dependent on diesel generators which have high capital, maintenance and fuel costs. This study provides an optimal sizing methodology for off-grid energy systems with storage. The method is verified with a Jordanian case study of two hybrid energy systems that are compared from a techno-economic perspective. PV arrays with battery or hydrogen energy storage were compared for an off-grid tourist camp in a remote Jordanian area. This study contributes comparisons between battery and hydrogen energy storage systems, considering the size, cost and reliability. The outcomes provide insights into optimal sizing for the combination of PV arrays and energy storage as well as the suitability of the technologies for such an application in a remote location in Jordan.

The remainder of this paper is structured as follows: Section 2 describes the operational optimisation method used for optimal sizing and the dynamic event tree (DET) used for the reliability assessment. Section 3 describes the case study input data. Section 4 presents the modelling results and discusses the insights in detail. Finally, Section 5 concludes the study, and suggests future work.

2 | METHODOLOGY

2.1 | Sizing optimisation

This section describes the sizing optimisation, which minimises the annualised cost of energy for a 100% renewable energy system. Given time series input data for the renewable generation and demand, the optimisation determines the renewable generating capacity, storage energy capacity and storage power rating. The methodology is a generalised linear programming problem that can be adapted to fit various demand, generation and storage configurations.

The optimisation objective function accounts for both the annualised capital cost and operation and maintenance (O&M) costs. The objective function is shown in Equation (1), with the following decision variable vector:

$$X = \left[\overline{P}^{\mathrm{ES}}, \overline{E}^{\mathrm{ES}}, \overline{P}^{R}, P_t^{\mathrm{ES,ch}}, P_t^{\mathrm{ES,dis}}, E_t^{\mathrm{ES}}, P_t^{R,\mathrm{curt}}\right],$$

where the variables are the energy storage power rating ($\overline{P}^{\mathrm{ES}}$), the energy storage energy capacity ($\overline{E}^{\mathrm{ES}}$), the renewable generation power rating ($\overline{P}^{R}$), the energy storage charging ($P_t^{\mathrm{ES,ch}}$) and discharging power ($P_t^{\mathrm{ES,dis}}$), the energy stored in the energy storage system (E_t^{ES}) and the curtailed power from renewable generation ($P_t^{R,\mathrm{curt}}$).

The first term of the objective function accounts for the annualised capital cost of renewable generation and energy storage power rating and energy capacity. The capital cost is annualised using Capital Recovery Factor (CRF), shown in Equation (2). The CRF accounts for asset lifetime and interest rates to give an annualised value for the capital cost [12]. The second term in Equation (1) accounts for the annual operating costs. These include the fixed and variable O&M costs for the renewable generation and energy storage. The optimisation is subject to several constraints. The first is the energy system power balance, shown in Equation (3).

$$\begin{aligned} \text{Min} \quad \Pi = & \left(\mathrm{CRF}^{R}\psi^{R}\overline{P}^{R} + \mathrm{CRF}^{\mathrm{ES}}\left(\psi^{\mathrm{ES}}\overline{P}^{\mathrm{ES}} + \psi^{\mathrm{ES}}\overline{E}^{\mathrm{ES}}\right)\right) \\ & + \Bigg(\mathrm{O\&M}^{R,F}\overline{P}^{R} + \mathrm{O\&M}^{R,V}\sum_{t=1}^{T}\left(P_t^{R}\right) \\ & + \mathrm{O\&M}^{\mathrm{ES},F}\overline{P}^{\mathrm{ES}} + \mathrm{O\&M}^{\mathrm{ES},V}\sum_{t=1}^{T}\left(P_t^{\mathrm{ES,dis}}\right)\Bigg) \end{aligned} \quad (1)$$

where

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n+1} \quad (2)$$

$$\left(P_t^R \overline{P}^R - P_t^{R,\mathrm{curt}}\right) + P_t^{\mathrm{ES,dis}} = P_t^{\mathrm{ES,ch}} + P_t^D \quad (3)$$

The power balance equation ensures all generated electricity is consumed or curtailment. Where, P_t^R is a normalised renewable generation profile, which is multiplied by the renewable power rating to give power generation in each time step. Renewable generation curtailment is assumed to be possible and is implemented through the power curtailment term. The following equations govern the battery operating limits and energy balance.

$$0 \le P_t^{\mathrm{ES,ch}} \le \overline{P}^{\mathrm{ES}} \quad (4)$$

$$0 \le P_t^{\mathrm{ES,dis}} \le \overline{P}^{\mathrm{ES}} \quad (5)$$

$$0 \le E_t^{\mathrm{ES}} \le \overline{E}^{\mathrm{ES}} \quad (6)$$

$$E_t^{\mathrm{ES}} = E^{\mathrm{ES,ini}} \overline{E}^{\mathrm{ES}} \Big|_{t=1} + E_{t-1}^{\mathrm{ES}} \Big|_{t>1} + \tau\left(P_t^{\mathrm{ES,ch}} \eta^{\mathrm{ES,ch}} - P_t^{\mathrm{ES,dis}} / \eta^{\mathrm{ES,dis}}\right) - E^{\mathrm{ES,SD}} \overline{E}^{\mathrm{ES}} \quad (7)$$

$$E_{t=T}^{\mathrm{ES}} \ge E^{\mathrm{ES,ini}} \overline{E}^{\mathrm{ES}} \quad (8)$$

Equations (4) and (5) ensure the energy storage charging and discharging powers stay within the inverter power limit. Equation (6) ensures the energy storage system operates within its energy capacity. Equation (7) ensures the continuity of stored energy in every time step. Equation (7) accounts for the initial energy ($E^{\mathrm{ES,ini}} \overline{E}^{\mathrm{ES}}$) in the first time step ($t = 1$) and the energy thereafter ($t > 1$). Additionally, the charging and discharging powers are multiplying by the time interval (τ) to convert to energy. The final term in Equation (7) accounts for the self-discharge of the battery over time ($E^{\mathrm{ES,SD}} \overline{E}^{\mathrm{ES}}$). Finally, Equation (8) ensures the final energy storage state of charge is equal to or greater than the initial state of charge.

The optimisation is a deterministic linear programming problem, rapidly solved (in <1 s), using commercial solvers. In this study, the problem was formulated in GAMS and solved using the GUROBI simplex solver.

2.2 | System reliability

Probabilistic safety assessment (PSA) is a systematic probabilistic methodology to assess the reliability and safety of complex systems [13, 14]. The event tree and the fault tree are two basic methods used in probabilistic safety assessment.

2.2.1 | Fault tree analysis

The fault tree analysis method assesses the impacts of combinations of undesired events in the context of system operation [15]. It is a widely used method for evaluating safety and reliability in system design and operation. Basic events and the top event are integrated by logical gates. The failure probability of the top event (P^{TE}) is given by Equation (9).

$$\mathrm{P}^{\mathrm{TE}} = \sum_{i=1}^{I} \mathrm{P}_i^{\mathrm{MCS}} - \sum_{i<j} \mathrm{P}_{i \cap j}^{\mathrm{MCS}} + \sum_{i<j<k} \mathrm{P}_{i \cap j \cap k}^{\mathrm{MCS}} - \dots + (-1)^{n-1} \mathrm{P}_{\bigcap_{i=1}^{I} i}^{\mathrm{MCS}} \quad (9)$$

In Equation (9), $\mathrm{P}_i^{\mathrm{MCS}}$ is the probability of each minimal cut set, which is the combination of the smallest number of basic events, which, if occur simultaneously, lead to the top event [15]. The simplified equations (Rare Event Approximation method) are used in this work.

$$\mathrm{P}^{\mathrm{TE}} = \sum_{i=1}^{I} \mathrm{P}_i^{\mathrm{MCS}}, \mathrm{P}_i^{\mathrm{MCS}} = \prod_{j=1}^{J} \mathrm{P}_j^{\mathrm{BE}} \quad (10)$$

In Equation (10), $\mathrm{P}_j^{\mathrm{BE}}$ is the failure probability of the basic event; m is the number of basic events in the minimal cut set.

2.2.2 | Dynamic event tree

Figure 2 shows the simulation flow diagram for the DET. A DET is an event tree in which branching can occur at different times [16]. It can describe the state evolution of a physical system driven by discrete random events and continuous system behaviours [17]. The DET analysis is performed as follows: (a) define the physical model of a system; (b) define the 'branching rules' to determine when a sequence should split, continue or terminate; (c) simulate DET; (d) analyse the resulting tree. The evolution of a DET starts from a predefined initial condition and each produced node can store information of a specific system state.

3 | CASE STUDY DEFINITION

The performance of the energy system sizing optimisation was demonstrated through a case study. In addition, the case study provides financial and reliability insights comparing two energy storage technologies: batteries and hydrogen storage. A lithium-ion battery chemistry was used for this study, due to its high efficiency, falling cost and high energy density. The hydrogen energy storage system was constructed with an electrolyser (to convert electricity to hydrogen), a compressor, storage tanks and a fuel cell (to convert hydrogen to electricity). Both the battery and hydrogen storage systems require DC to DC converters to manage charge power, discharge power and voltage.

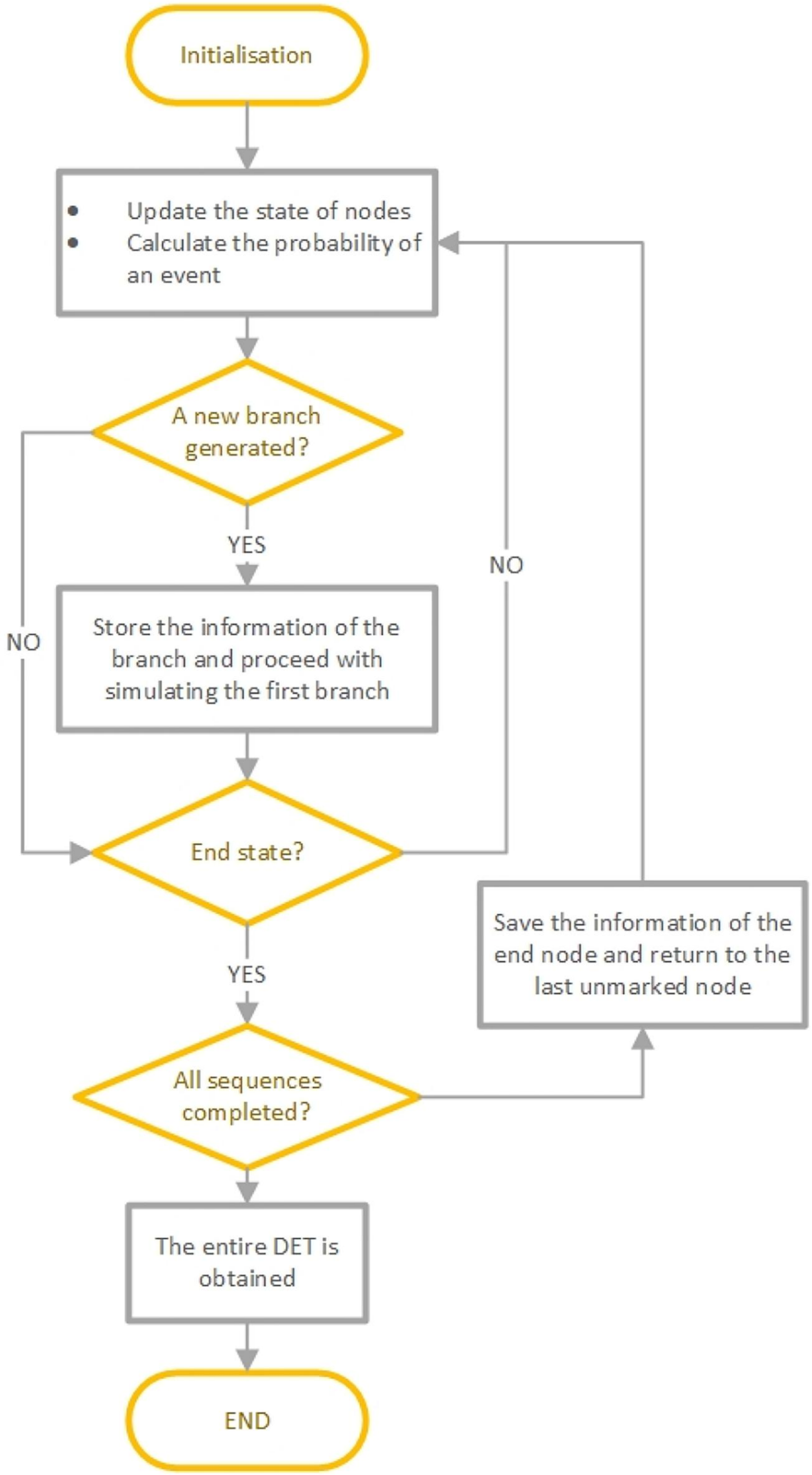

FIGURE 2 Dynamic event tree (DET) simulation flow diagram.

The power flow diagram for the battery and hydrogen storage systems are shown in Figure 3. In Figure 3, the DC to DC converter after PV generation performs maximum power tracking. The power flow schematics illustrate component design. However, only the power flows are considered in the optimisation, not the individual components.

3.1 | Technical inputs

The off-grid power system was based on a luxury campsite in Jordan, aiming to replace the existing diesel generators with a zero-emission alternative. The campsite is in the Wadi Rum Reserve region of Jordan and has an excellent solar resource.

Therefore, PV panels were chosen as the power generation technology. The normalised PV generation profile is shown in Figure 4a.

The campsite requires electricity for air conditioners, extractor fans, fridge-freezers, lights, kettles etc. The demand for electricity was measured hourly for a single day, daily for a whole month and monthly for a full year. This data was used to produce an hourly demand input profile for the time horizon of a year. The demand profile is shown in Figure 4b.

The power rating and energy capacity of the energy storage systems were variables, chosen by the optimisation. The energy storage charging and discharging efficiencies and self-discharge are shown in Table 1. The battery had a 90% round-trip efficiency [21], which was applied to the charging and discharging process as the square root of the round-trip efficiency (94.87%). The battery experiences self-discharge over time, reducing energy stored in the battery by 0.00206% of total energy capacity per hour. The hydrogen charging and discharging efficiencies were give as typical electrolyser and fuel cell efficiencies.

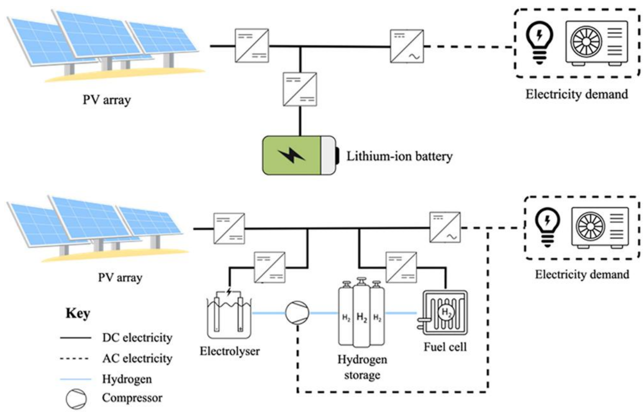

FIGURE 3 Power flow diagrams for battery (top) and hydrogen (bottom) energy systems, including key components [18].

3.2 | Economic inputs

The economic inputs for PV and energy storage are shown in Table 2. The PV panels were assumed to have a lifetime of 30 years, giving a CRF of 0.1061. The hydrogen storage was

TABLE 1 Energy storage efficiency inputs.

Technical characteristics	Battery	Hydrogen
Charging efficiency (%)	94.87	72 [19]
Discharging efficiency (%)	94.87	60 [20]
Self-discharge (%/h)	0.00206	0

TABLE 2 PV and energy storage economic inputs.

	PV	Battery	Hydrogen
Economic costs			
Power rating capital cost (£/kW)	524 [22]	520 [23]	3000 [24]
Energy capacity capital cost (£/kWh)	-	128	5 [24]
Fixed O&M cost (£/kW/year)	0	0	60 [25]
Variable O&M cost (£/kWh)	0	0.128	0
Capital recovery factor inputs			
Lifetime (years)	30	10	30 [26]
Discount rate (%)	10	10	10
CRF (–)	0.1061	0.1627	0.1061

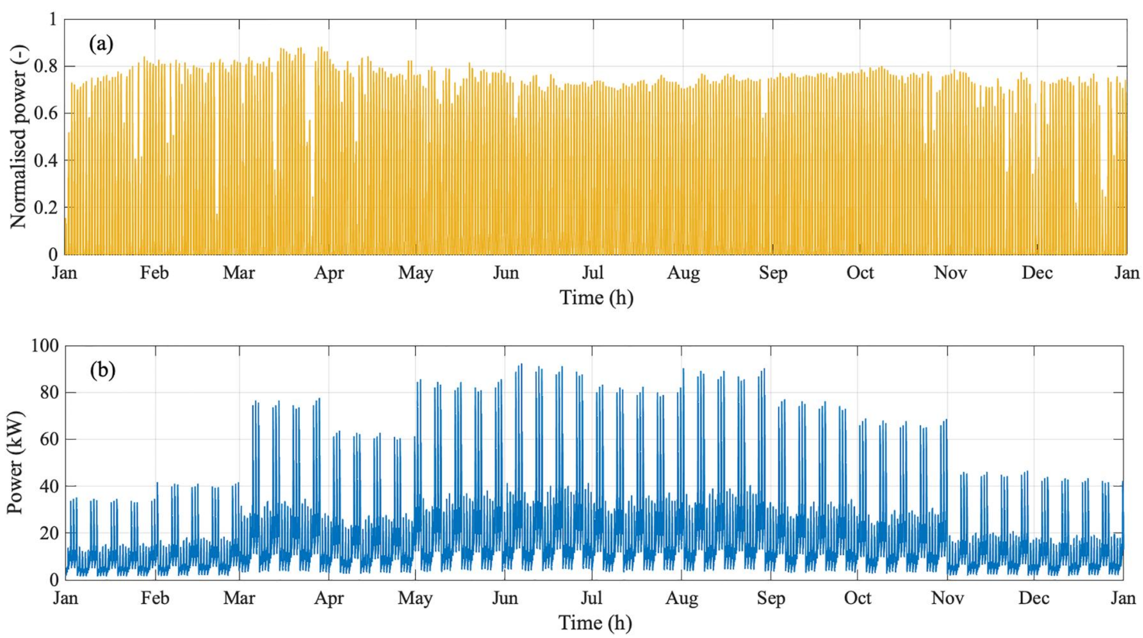

FIGURE 4 Hourly time series input data for (a) normalised PV generation and (b) local demand.

subject to a fixed O&M cost of £60/kW/year. Battery storage systems experience energy capacity degradation from charging and discharging, called cycle aging. The cost of cycle aging was accounted for by applying a variable O&M cost of £0.128/kWh. This assumed 1000 full cycles before the battery reached end-of-life. The battery was assumed to have a 10-year lifetime, giving a CRF of 0.1627. Hydrogen energy storage degradation was neglected but a 30 year lifetime was assumed, giving a CRF of 0.1061.

3.3 | Limited diesel generation case study

During times of low renewable generation, a 100% renewable energy system must have sufficient storage capacity to meet demand requirements. Therefore, 100% renewable energy systems often require oversized energy storage, leading to high capital costs, low storage utilisation and high renewable energy curtailment.

Alternative options are available to mitigate the most extreme cases of low renewable generation. Firstly, demand curtailment can reduce energy demand while renewable generation is low. Therefore, reducing the energy storage capacity required to satisfy demand. In the limited diesel generation case study, a small amount of generation from an existing diesel generator was made available to mitigate low renewable generation.

The following terms were added to the objective function (1). All numerical inputs are real data from the existing diesel generator at the campsite in Jordan.

$$\sum_{t=1}^{T} \tau K^{D} \left(\frac{P_t^{\mathrm{DG}}}{\mu^{\mathrm{DG}}} \right) + \mathrm{O} \,\&\, \mathrm{M}^{\mathrm{DG},F} \tag{11}$$

The first extra term defines the cost of diesel generation, where the price of diesel ($K^D = £0.063/\mathrm{kWh}$) is multiplied by the diesel generating power (P_t^{DG}) over the diesel generator efficiency ($\mu^{\mathrm{DG}} = 35\%$). The second extra term is the annual fixed O&M cost ($O \,\&\, M^{\mathrm{DG},F} = £1,878.72$). Two constraints were also added.

$$P_t^{\mathrm{DG}} \leq 105 \text{ kW} \tag{12}$$

$$\sum_{t=1}^{T} \tau \left(P_t^{\mathrm{DG}} \right) = \overline{E}^{DG} \tag{13}$$

The first additional constraint Equation (12) limits the diesel generator power to 105 kW. The second additional constraint Equation (13) limits the annual energy generated by the diesel generator. Where $\overline{E}^{\mathrm{DG}}$ is a fixed input value that is varied for the case study. The minimum up/down and minimum stable generating characteristics of the diesel generator are neglected.

4 | RESULTS AND DISCUSSION

4.1 | Sizing optimisation

4.1.1 | Optimal power and energy

The results for PV and energy storage sizing are shown in Figure 5, for the battery and hydrogen storage scenarios. The power rating was identical for battery and hydrogen storage systems. This is sensible as the storage power rating ensures peak power demand can be met, without costly excess power capacity. The energy capacity for hydrogen storage was significantly higher than for the battery storage. The difference was due to significantly different energy capacity capital costs. The hydrogen storage system resulted in a higher PV power rating. This occurred due to the difference in round-trip efficiencies, which were 90% and 43.2% for the battery and hydrogen systems respectively. The hydrogen scenario's PV power rating was higher to compensate for higher charging and discharging efficiency losses. Figure 5 provides a generalised result for similar campsite case studies in Jordan. With a known peak demand, outputs for optimal PV power rating and energy storage power rating and energy capacity are given. This result demonstrates the capability of the optimisation model to find the optimal sizing of a 100% renewable energy system for various technologies.

4.1.2 | Annualised cost

The annualise cost of energy was the optimal output value of the optimisation, given by Equation (1). The final annualised cost of energy for the battery and hydrogen energy systems are compared in Figure 6, for a range of peak demands. Figure 6 shows increasing annualised cost with increasing peak demand and a higher annualised cost for battery storage. Although hydrogen has a high capital cost for the electrolyser, the energy

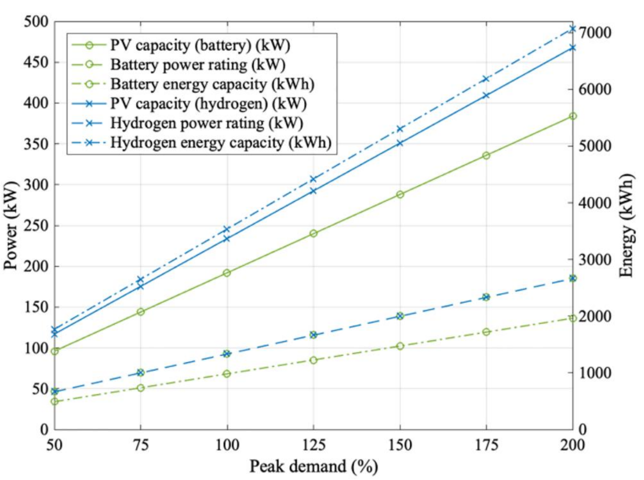

FIGURE 5 Optimal PV power rating and energy storage power rating and energy capacity. Results given for a range of peak demands, relative to 92.5 kW at 100%.

storage capacity has a very low cost. This result shows the implications of the capital cost structure and highlights the need for accurate cost inputs. Additionally, the annualised cost for battery and hydrogen scenarios are similar overall.

4.1.3 | Generation and demand imbalance

Demand was summed for each 24-h period and subtracted from the sum of PV generation for each 24-h period. The result was the imbalance between PV generation and demand for each day of the time horizon, shown in Figure 7. The results show there was mostly more PV generation than demand in each day. However, occasionally demand was higher than PV generation. This occurred on 9 days for the battery system and 7 days for the hydrogen system (this difference was due to different PV generation capacities). This result demonstrates the need for multiple day energy storage (at least 48-h), to be able to meet demand during times of low PV generation. Supplying demand in this 100% renewable energy system is not only intraday storage but requires multiple day storage.

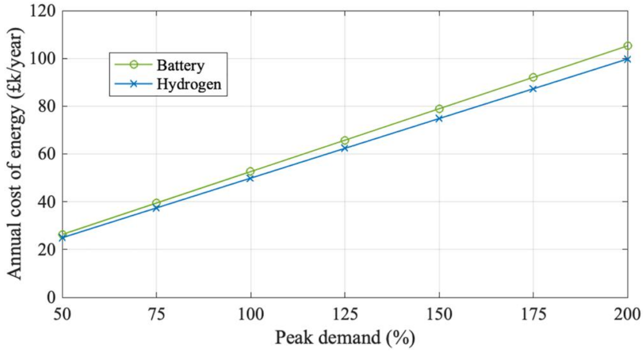

FIGURE 6 Annualised cost of energy for the 100% renewable energy system. Results given for a range of peak demands, relative to 92.5 kW at 100%.

4.1.4 | Energy system efficiency

Figure 8 presents the battery and hydrogen systems monthly PV energy generation divided in three destinations: curtailment, loss from charging/discharging and utilisation to meet demand. The normalised PV generation input was identical for both technologies. Therefore, their generation profiles over the year were identical. However, the PV capacity chosen by the optimisation was higher for the hydrogen system, leading to higher PV generation in every month.

The first possible destination for PV generation was curtailment. Given by the dark section at the bottom of each bar, Figure 8 shows the battery system has higher PV energy curtailment than the hydrogen system. In fact, approximately 52.5% of PV generation was curtailed in the battery scenario, compared to 31.4% for hydrogen. The second possible

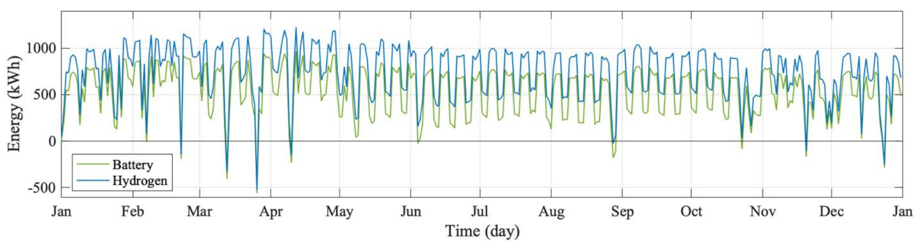

FIGURE 7 Daily energy imbalance between PV generation and demand over the year time horizon. Calculated by subtracting the daily sum of demand from the daily sum of PV generation. Where positive values show a surplus of energy and negative values show a shortfall.

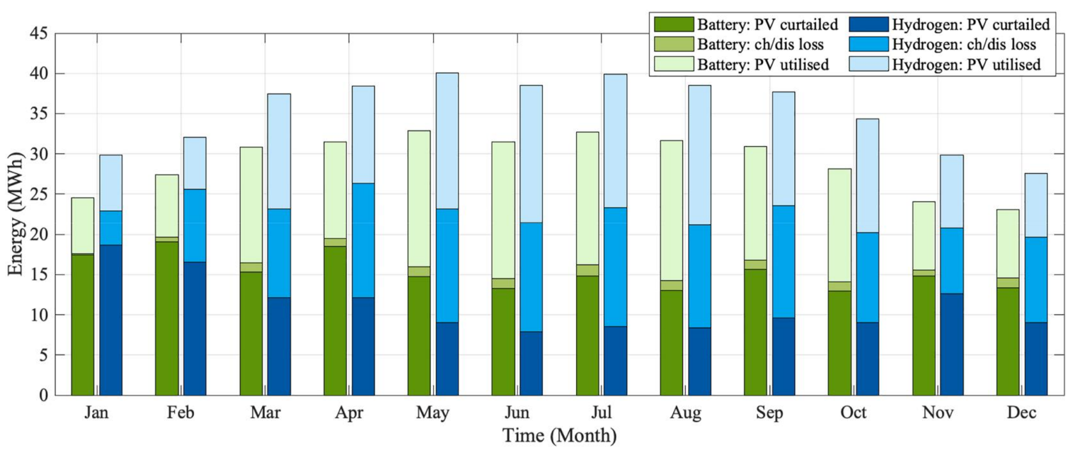

FIGURE 8 Monthly PV energy generation divided into three destinations: curtailment, charge/discharge losses, and utilisation to meet demand.

destination for PV generation was charging and discharging losses. Shown by the middle section of each bar in Figure 8, the efficiency of the battery was significantly higher than hydrogen. Combining efficiencies for electrolysis, compression and fuel cell conversion gave a round-trip efficiency of 43.4% for hydrogen storage, leading to high energy losses. Consequently, the overall energy wasted by the hydrogen system was higher than the battery system (given by summing PV curtailment and charge/discharge losses). The overall efficiencies of the battery and hydrogen systems were 44.1% and 36.0% respectively.

The results in Figure 8 demonstrate the difference in energy wasted for the battery and hydrogen energy systems. Although more energy is curtailed in the battery system, higher efficiency losses result in high levels of energy wasted for the hydrogen system. In both cases, over half the PV generation is wasted. This result also justifies the need for a higher capacity of PV generation in the hydrogen system, to compensate for higher losses.

4.1.5 | Energy storage state of charge

The battery and hydrogen storage state of charge is shown in Figure 9, from 0 to 1, for the full year time horizon. This result shows the battery storage system going through small charge/discharge cycles for most of the year, regularly using all stored energy and returning to an empty state of charge 407 times. The battery storage system was used for short term storage of PV generation. Whereas the hydrogen storage system maintains some stored energy for many weeks, reaching an empty state of charge 70 times. Therefore, hydrogen storage was used for long term energy storage. This result demonstrates the key practical difference between battery and hydrogen storage operation and highlights the importance of accounting for the batteries self-discharge. While hydrogen can store energy indefinitely, battery storage will lose stored energy over time due to self-discharge, making battery storage suited to short term applications and hydrogen storage suited to longer term applications.

4.1.6 | Limited diesel generation

The annualised cost of energy for battery and hydrogen energy systems in shown in Figure 10, for a range of diesel energy generation limits. The solid lines are the results with diesel generation available and the dotted lines are the previous results (for a peak demand of 92.5 kW) with all diesel generators decommissioned.

A key feature of adding any diesel generation is the inclusion of the associated fixed O&M cost. Consequently, the annualised cost of energy increased when diesel generation was made available but not used. This is evident in Figure 10, as both solid lines are higher than their respective dotted lines where maximum diesel generation is 0 MWh.

Introducing some diesel generation to the battery energy system rapidly reduced annualised cost of energy. Moreover, the battery energy system required approximately 0.1 MWh of diesel generation (1 h of diesel generation at rated capacity) to compensate for the fixed O&M cost. On the contrary, diesel generation effected a steady fall in annualised cost of energy for the hydrogen system. Consequently, a higher diesel generation of approximately 4 MWh (40 h of diesel generation at rated capacity) was required to compensate for the fixed O&M cost.

Another key outcome from Figure 10 is a significant change in the annualised cost comparison between the battery and hydrogen systems. In Figure 6, the hydrogen system had the lower annualised cost of energy. Whereas a steady fall for the hydrogen system and a rapid drop for the battery system gave the battery system the lower annualised cost of energy after 0.25 MWh of diesel generation (2.5 h of diesel generation at rated capacity). Furthermore, at 5 MWh of diesel generation

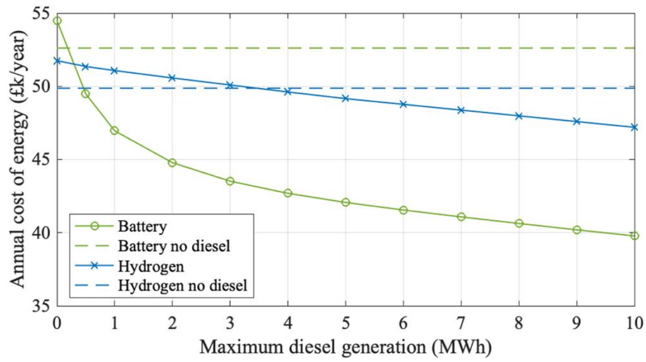

FIGURE 10 Annualised cost of energy with increasing diesel generation (solid lines) and with no diesel generation available (dotted lines). Results given for a peak demand of 92.5 kW.

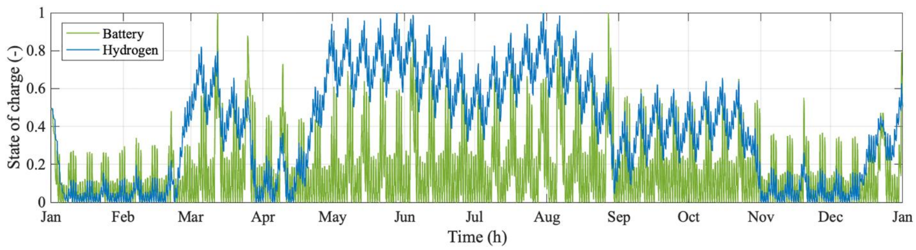

FIGURE 9 Energy storage system state of charge, between 0 and 1, for the full year time horizon. The battery capacity was 982 kWh and the hydrogen capacity was 3,537 kWh.

(50 h of diesel generation at rated capacity), the battery system was cheaper by £7,100 per year.

The result in Figure 10 demonstrates that the hydrogen system is capable of mitigating low renewable generation without excessive additional costs. Therefore, utilising existing diesel generators to support the hydrogen system is only marginally beneficial. In contrast, guaranteeing demand during low renewable generation with a battery storage system resulted in costly oversizing and low utilisation. Therefore, a very small contribution from a diesel generator is extremely beneficial for the battery system. Unfortunately, diesel generation increases the greenhouse gas emissions of the off-grid energy system. Alternatively, introducing demand curtailment, with an associated cost, would have the same effect, without adding any greenhouse gas emissions.

4.2 | Reliability

Fault tree analysis of battery and hydrogen energy systems was carried out for two scenarios.

1. No power supply from the PV panels and the energy storage cannot meet power demand.
2. PV panels fail but storage can supply demand.

The fault trees are shown in Figure 11.

The outputs for the fault tree analysis are the R values shown in Table 3.

From the perspective of system reliability, the battery system is more reliable as the hydrogen energy system has more components which increases the failure probability. However, as we considered the storage capacity of battery system and hydrogen system, the real-time supply reliability of the hydrogen storage system is higher than that of the battery system. This is because the resilience of hydrogen storage system is stronger as the capacity of energy storage is higher. For systems such as the Jordan campsite analysed in this case study, reliability of power supply is highly regarded. With no connection to the grid, or alternative source of power, the reliability is an important part of designing the 100% renewable energy system. These results highlight the differences in reliability of the battery and hydrogen systems and show that not only annualised cost but also the ability for each system to continuously provide sufficient power should be considered before any investment decision is made.

5 | CONCLUSION

This study presents an off-grid 100% renewable energy system sizing methodology that determines the power rating of on-site renewable generation as well as the power rating and energy capacity of on-site energy storage. The general methodology allows adaptation for any off-grid energy system with on-site generation, demand and energy storage. The optimisation minimises annualised cost of energy using the

TABLE 3 *R* values as outputs from fault tree analysis.

	Scenario 1	Scenario 2
Battery	0.00050349825	$3.50229999 \times 10^{-6}$
Hydrogen	0.00050349825	$3.52599986 \times 10^{-6}$

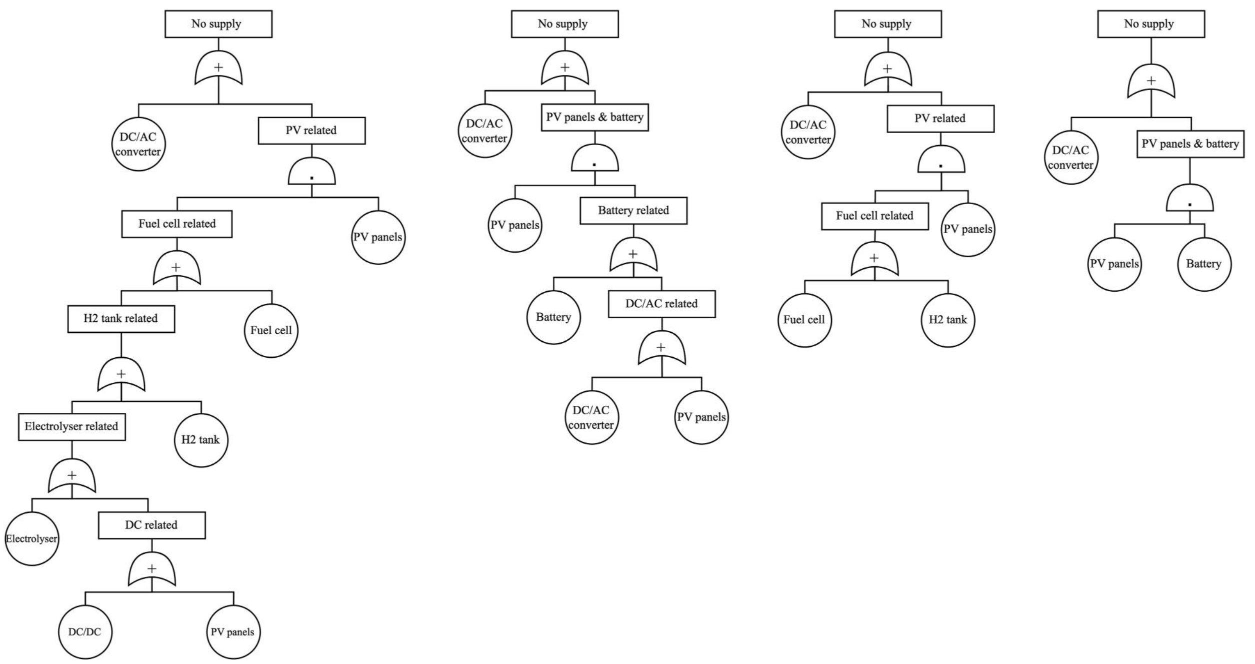

FIGURE 11 The fault trees from the fault tree analysis for the battery and hydrogen energy storage systems shown for: (left) Scenario 1 hydrogen, (left middle), Scenario 1 battery (right middle) Scenario 2 hydrogen and (right) Scenario 2 battery.

capital cost of each technology and the operation and maintenance costs. The methodology was applied to a case study of a campsite in Jordan, with existing diesel generators. A 100% renewable energy system was analysed from economic and environmental perspectives. The reliability of the renewable energy system design was also considered due to its high priority for off-grid systems that cannot rely on electricity from a central power grid. The methodology was applied to two energy storage technologies: battery and hydrogen. In an alternative case study, limited diesel generation was made available to support occasional low renewable generation.

The results show the methodology is suitable for finding the optimal renewable generation and energy storage sizes. For a 100% renewable energy system, hydrogen storage had a lower annualised cost of energy with £49,873/year, compared to battery storage with £52,614/year. On some days, total energy demand was greater than total PV generation. Therefore, storage capacity was required for multiple days, leading to oversizing and low utilisation of the battery. The result was excessive battery capital costs, necessary to meet existing demand. Including diesel generation rapidly reduced the annualised cost of energy, where 5 MWh of diesel generation reduced the cost by £10,548/year or 20%, making the battery system more economical than the hydrogen system. The results show that a small amount of diesel generation is very beneficial for the battery system but introduces greenhouse gas emissions. However, where demand curtailment is used instead of diesel generation, these emissions can be avoided. Finally, analysis showed that the battery system is more reliable, as the hydrogen system has more components. However, the large capacity of hydrogen makes the real-time reliability higher than the battery system.

Although some diesel generation was considered in this study, the operating limitations were neglected. Considering these may provide insights into the capability of diesel generators playing such a small role in generation. Additionally, replacing diesel generation with demand curtailment offers a zero carbon alternative. Future work could investigate the campsite demands, quantify opportunities for demand curtailment and allocate a price. Alternatively, research could quantify the diesel generation emissions and compare this with the reduction of embedded emissions caused by smaller PV and energy storage. Finally, this work assumes a connection to grid is not possible. Future work could consider the cost of building infrastructure necessary to connect the campsite to a central electricity grid.

ACKNOWLEDGEMENTS

The authors would like to thank the Royal Academy of Engineering for funding this research through the Engineering X Transforming Systems through Partnership programme, project number TSP2021\100334.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

ORCID

William Seward https://orcid.org/0000-0001-6153-686X

REFERENCES

1. Solargis: Solar resource maps of Jordan. Download Solar Resource Maps and GIS Data for 200+ Countries and Regions (2020). https://solargis.com/maps-and-gis-data/download/jordan. Accessed 26 Sep 2022
2. Bhattacharyya, S.C.: Mini-grid based electrification in Bangladesh: technical configuration and business analysis. Renew. Energy 75, 745–761 (2015). https://doi.org/10.1016/j.renene.2014.10.034
3. Iskanderani, A.I.M., et al.: Analyzing the off-grid performance of the hybrid photovoltaic/diesel energy system for a peripheral village. Int. J. Photoenergy 2020, 1–15 (2020). https://doi.org/10.1155/2020/7673937
4. Hermann, D.T., et al.: Techno-economic and environmental feasibility study with demand-side management of photovoltaic/wind/hydroelectricity/battery/diesel: a case study in Sub-Saharan Africa. Energy Convers. Manag. 258, 1–20 (2022)
5. Sen, R., Bhattacharyya, S.C.: Off-grid electricity generation with renewable energy technologies in India: an application of HOMER. Renew. Energy 62, 388–398 (2014). https://doi.org/10.1016/j.renene.2013.07.028
6. Madziga, M., Rahil, A., Mansoor, R.: Comparison between three off-grid hybrid systems (solar photovoltaic, diesel generator and battery storage system) for electrification for gwakwani village, South Africa. Environments 5(5), 1–21 (2018). https://doi.org/10.3390/environments5050057
7. Zieba Falama, R., et al.: A case study of an optimal detailed analysis of a standalone photovoltaic/battery system for electricity supply in rural and remote areas. Int. Trans. Electr. Energy Syst. 2022, 1–12 (2022). https://doi.org/10.1155/2022/7132589
8. Kumar, R., Channi, H.K.: A PV-Biomass off-grid hybrid renewable energy system (HRES) for rural electrification: design, optimization and techno-economic-environmental analysis. J. Clean. Prod. 349, 1–15 (2022). https://doi.org/10.1016/j.jclepro.2022.131347
9. Abd El-Sattar, H., et al.: Optimal sizing of an off-grid hybrid photovoltaic/biomass gasifier/battery system using a quantum model of Runge Kutta algorithm. Energy Convers. Manag. 258, 1–19 (2022). https://doi.org/10.1016/j.enconman.2022.115539
10. Al Afif, R., Ayed, Y., Maaitah, O.N.: Feasibility and optimal sizing analysis of hybrid renewable energy systems: a case study of Al-Karak, Jordan. Renew. Energy 204, 229–249 (2023). https://doi.org/10.1016/j.renene.2022.12.109
11. Al-Addous, M., et al.: Performance analysis of off-grid PV systems in the Jordan Valley. Renew. Energy 113, 930–941 (2017). https://doi.org/10.1016/j.renene.2017.06.034
12. Daggett, A., Qadrdan, M., Jenkins, N.: Feasibility of a battery storage system for a renewable energy park operating with price arbitrage. In: 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), pp. 1–6 (2017)
13. Zio, E.: The future of risk assessment. Reliab. Eng. Syst. Saf. 177, 176–190 (2018). https://doi.org/10.1016/j.ress.2018.04.020
14. Aven, T.: Foundational issues in risk assessment and risk management. Risk Anal. An Int. J. 32(10), 1647–1656 (2012). https://doi.org/10.1111/j.1539-6924.2012.01798.x
15. Volkanovski, A., Čepin, M., Mavko, B.: Application of the fault tree analysis for assessment of power system reliability. Reliab. Eng. Syst. Saf. 94(6), 1116–1127 (2009). https://doi.org/10.1016/j.ress.2009.01.004
16. Acosta, C., Siu, N.: Dynamic event trees in accident sequence analysis: application to steam generator tube rupture. Reliab. Eng. Syst. Saf. 41(2), 135–154 (1993). https://doi.org/10.1016/0951-8320(93)90027-v
17. Chi, L., et al.: Integrated deterministic and probabilistic safety analysis of integrated energy systems with bi-directional conversion. Energy 212, 1–13 (2020). https://doi.org/10.1016/j.energy.2020.118685

18. Messenger, R.A., Abtahi, A.: Photovoltaic Systems Engineering, 4th ed. CRC press (2018)
19. Dias, V., et al.: Energy and economic costs of chemical storage. Fundamental Characterization and Performance of Alternative Fuels, 6 (2020). https://doi.org/10.3389/fmech.2020.00021
20. Fuel Cell Technologies Office. Fuel Cells. Energy Efficiecny and Renewable Energy. (2015). https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf. [Accessed: 26-Sep-2022]
21. Hicks, C., Baghzouz, Y.: Experimental steady-state and transient analysis of a behind-the-meter battery storage for residential customers with PV systems. In: 2019 International Conference on Clean Electrical Power (ICCEP), pp. 438–443 (2019)
22. National Grid ESO: Future Energy Scenarios 2020 Costing Data Workbook. Warwick (2020)
23. Bullard, N.: This Is the Dawning of the Age of the Battery. Bloomberg Green (2020). https://www.bloomberg.com/news/articles/2020-12-17/this-is-the-dawning-of-the-age-of-the-battery. Accessed 01 Feb 2021
24. European Association for Storage of Energy. Chemical Energy Storage: Hydrogen. (2021). https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_Hydrogen.pdf. Accessed 26 Sep 2022
25. Langels, H., Syrjä, O.: Hydrogen Production and Storage Optimization Based on Technical and Financial Conditions. Uppsala (2021)
26. BEIS: Hydrogen Production Costs 2021. London (2021)

How to cite this article: Seward, W., et al.: Sizing, economic and reliability analysis of photovoltaics and energy storage for an off-grid power system in Jordan. IET Energy Syst. Integr. 1–12 (2023). https://doi.org/10.1049/esi2.12108