Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities

Jhud Mikhail Aberilla, Alejandro Gallego-Schmidt, Laurence Stamford, Adisa Azapagic

Abstract

Small-scale off-grid renewable energy systems are being increasingly used for rural electrification, commonly as stand-alone home systems or community micro-grids. With the variety of technologies and configurations available, it is not clear which options are sustainable for remote communities. This study investigates the life cycle environmental sustainability of both home and community installations, designed as part of this work, which utilise diesel, solar, and wind resources coupled with battery storage. A total of 21 system configurations (six home systems and 15 micro-grids) have been designed and optimised for a prototypical rural community in the Philippines, considering both stand-alone and hybrid systems. Life cycle assessment (LCA) considering 18 potential impact categories has been carried out to compare the environmental impacts associated with electricity production of each option. At the household level, hybrid solar photovoltaics (PV)-wind systems with storage have 17–40% lower impacts than the equivalent stand-alone installations per kWh generated. Batteries are a major environmental hotspot, causing up to 88% of the life cycle impacts of a home energy system. Among the community micro-grid options, the PV-wind-lead acid battery hybrid system has the lowest impacts in many categories, including climate change, ozone depletion, and acidification. Comparing equivalent architectures for single-household and community-scale installations, PV systems are environmentally more sustainable if installed individually in households, while larger turbines in community micro-grids are environmentally better for wind utilisation. The results suggest that a household-scale PV system integrated within a micro-grid with community-scale wind turbines and Li-ion batteries is environmentally the most sustainable configuration.

1. Introduction

As the cornerstone of modern society, access to energy has been linked to improvements in health, education, and social welfare [1]. It is also acknowledged by the Sustainable Development Goals set by the United Nations that the provision of affordable and clean energy (Goal 7) is interconnected with other milestones in poverty elimination, environmental protection, and peace [2]. However, there are still over a billion people worldwide, 87% of which are in rural areas, without electricity [3,4]. Many are still dependent on traditional biomass and imported fossil fuels (e.g. kerosene, diesel) for their energy needs. While there have been great efforts in addressing this gap, the energy problem remains a challenge due to the interplay between technology, economics, the environment, and society.
Solutions to provide electricity in rural areas may be classified as large-scale grid extension or small-scale (localised) distributed generation. Furthermore, off-grid systems can be classified based on the number of supply and demand connections (Table 1) [5]. For the governments of developing nations, an immediate answer to improving rural electrification rates is the extension of the grid [6]. However, technical or economic constraints may prove grid extension unviable. In this case, off-grid installations are deployed. Historically, this has been achieved by diesel generators [6]. More recently, with greater environmental awareness as well as concerns over energy security, policy makers and other stakeholders have shown a growing interest in alternative energy sources for rural electrification [7].

Renewable energy (RE) is recognised as a significant part of rural electrification plans. The International Energy Agency (IEA) recommends that by 2030, 60% of new capacity (equivalent to 571 TWh) for rural areas around the world be supplied by renewables [8]. IEA also expect that 70% of rural connections will be off-grid by the same year. The World Bank also finds that several RE technologies (e.g. wind and biomass) are more economical than diesel or gasoline generators for off-grid applications, especially at smaller scales [9]. With the significant potential of RE sources and the global shift towards cleaner energy, it is no surprise that studies on the design and optimization of off-grid RE systems are widespread in academic and technical literature, as discussed in the next section.

However, given the variety of technology options and system architectures available commercially, it is not clear which types of off-grid systems are feasible and sustainable for remote communities. To address this knowledge gap, this study explores for the first time both household-scale and community-scale options for off-grid power generation. The main aim is to design autonomous small-scale power systems and evaluate their life cycle environmental sustainability depending on the system configuration in terms of technology selection and installation scale. The technologies considered for both home- and community-scale systems comprise solar photovoltaics (PV), wind turbines, diesel generators and batteries. By quantifying the impacts of these technologies integrated within differing system designs and operating at different scales, the study also aims to provide an insight into the role of energy access for the environmental sustainability of developing rural areas. The results from this research complement previous techno-economic analyses discussed below, aiming to further inform stakeholders of rural electrification.

### 2. Literature review

Previous studies have investigated different scales for off-grid power systems; however, they were typically limited to techno-economic analyses. For example, Chaurey and Kandpal [10] used life cycle costing to compare home solar PV systems with PV micro-grids. They found that the costs were influenced mostly by consumption levels and user density. Mainali and Silveira [11] come to similar conclusions for the cases of Nepal and Afghanistan, although they compared different technologies at each scale. In a study focusing on business models, D’Agostino et al. [12] found that there was a trade-off between the economic viability and consumer satisfaction. Rojas-Zerpa and Yusta [13] expanded the scope further to consider some other social aspects as well as environmental pollution, alongside the economic criteria in a comparison of decentralised and centralised generation systems based in a village in the Venezuelan Andes.

A recent review [5] found that the systems most studied for techno-economic feasibility were hybrid micro-grids due to the flexibility of solutions and approaches that could be used. The software package HOMER [14], primarily aimed for small off-grid systems, was identified as the most commonly used for the modelling and optimisation of energy systems in remote areas [5,15]. A comparison of HOMER with other software tools and algorithms showed that their respective results were quite similar [16,17], with HOMER having the advantage in terms of input flexibility and user interface.

In addition to techno-economic performance, several studies also considered the environmental impacts of RE systems using life cycle assessment (LCA) [18], with most focusing on greenhouse gas (GHG) emissions in a European context [19]. Reviews on life cycle GHG emissions suggest that environmental impacts of RE systems are strongly dependent on scale and location, both of which also affect the generation capacity of the system [20,21]. The effect of ‘numbering up’ and ‘scaling up’ on life cycle energy and emissions was also studied previously, focusing on wind turbines to estimate ozone depletion, acidification, and global warming potentials of various installation schemes [22]. However, comprehensive environmental assessment of RE technologies considering multiple environmental impacts across the whole life cycle of the system, are limited in the literature [23].

In addition to publications on single-source energy systems, there is a small body of LCA literature on small-scale hybrid systems. For instance, Smith et al. carried out an LCA study of a diesel-PV-wind-battery micro-grid for an island community in Thailand [24]. They showed that maximising the RE fraction in the micro-grid does not automatically equate to better environmental performance. Another LCA study on hybrid PV systems in a village in Kenya also found similar environmental trade-offs between solar PV and diesel generators [25]. On a smaller scale, Balcombe et al. [26] assessed the environmental impacts of an integrated PV-Stirling engine-battery system designed to meet domestic energy requirements in the UK. They showed that appropriate battery sizing and management is crucial for optimal environmental benefits. In a different study, the LCA of nine hybrid power options for a mobile house investigated combinations of solar PV and wind power with diesel and hydrogen fuel cells as backup [27]. Wind turbines were found to be more environmentally favourable than solar PV, and that batteries contributed a significant share of the total impacts. These studies illustrate that small-scale hybrid systems can be environmentally advantageous over stand-alone technologies, but not without trade-offs.

Thus far, LCA studies on small-scale RE systems focused on a chosen scale of implementation, such as a single residence or a village. In comparative studies, most authors evaluated the RE system of interest against the existing grid. For example, Kabakian et al. [28] compared the environmental impacts of household-scale PV installations, with and without batteries, to the Lebanese electricity system. Similarly, Smith et al. [24] and Balcombe et al. [26] compared their systems with the Thai and UK electricity grid, respectively. As far as the authors are aware, there have been no integrated studies on the environmental impacts of rural electrification across different scales of distribution, specifically, stand-alone home systems vs community micro-grids. This is in contrast with a significant body of literature on the techno-economic comparisons of home energy systems with community micro-grids.

The next section details the design of the systems developed in this work, followed by the LCA methodology applied to evaluate their environmental sustainability. The results are presented and discussed in Section 4 and conclusions in Section 5.

---

**Table 1**

| Number of consumers | Number of energy sources | Single | Multiple |
|---------------------|--------------------------|--------|----------|
| Single              | Stand-alone system       | Hybrid energy system |
| Multiple            | Decentralised micro-grid | Distributed hybrid micro-grid |

**Section 4 and conclusions in Section 5.**
3. Methodology

3.1. Design of household- and community-scale power systems

Different configurations of the hybrid systems considered for single household installations and community micro-grids are shown in Fig. 1. To determine the component sizes for each configuration which are able to satisfy the household and community loads, a prototypical rural community of 50 households is assumed as the context for the study. With the goal of fostering socio-economic development of remote off-grid communities, the system options have been sized to supply the demand of households with advanced access to electricity, equivalent to 3000 kWh/household/year [29]. The remote communities considered here are taken to be represented by island communities. Since most inhabited islands are in tropical regions [30], this climatic area is chosen as the representative condition of off-grid island communities. A rural community in the Philippines is considered as an example for these purposes. A typical residential load profile (Fig. 2) is assumed with an hourly and daily variability of 10% and 20%, respectively. This scenario is similar to other representative locations in off-grid renewable energy studies [31–34].

The technologies considered are limited to commercially available sizes of diesel generators, solar PV panels, and micro-wind turbines. Since the system is expected to operate continuously with varying loads (i.e. as the main energy provider rather than a standby unit), only diesel generators with capacities greater than 8 kW are considered. This means that they are not suitable for stand-alone installation in single households and, hence, diesel generators are not considered at that scale. Instead, solar PV and wind turbines are integrated with battery storage to ensure that the household’s electricity needs are fully met. As in previous studies, which focused on techno-economic implications, installed capacities of 5 and 100 kW are considered for micro-wind turbines [22]. Polycrystalline silicon panels are mounted on roofs for household-scale and ground-mounted in community-scale installations.

The sizing of the solar PV and wind turbines is based on the solar and wind resource data from the NASA Surface Meteorology and Solar Energy database [35] for the (tropical) location 11°N, 120°E. This corresponds to an annual average solar insolation of 5.27 kWh/m²/day and an annual average wind speed (at 50 m above the ground) of 5.66 m/s. To ensure continuous power supply, a lead-acid or Li-ion battery is included in the system. For the centralised community micro-grid options, a 1-km distribution network is added to cover 50 households in a 7-ha area.

The HOMER Pro software [14] has been used for system design and component sizing. HOMER has been chosen since its optimisation and sensitivity analysis allow quick evaluations of multiple options. As mentioned earlier, it has also been used in various other studies of hybrid energy systems due to its flexibility and the broad range of components available in the software [16,36]. The results of the system design and optimisation are discussed in the results section. Prior to that, the LCA methodology used to evaluate the environmental sustainability of different system designs is described next.

3.2. LCA methodology

The LCA study has been conducted according to the guidelines in ISO14040/44 [37,38]. An attributional approach has been followed as the study is focused on comparative analysis of a micro-economic activity. The following sections describe the goal and scope of the study, inventory data and the impact assessment method used to estimate the environmental impacts.

3.2.1. Goal and scope

The goal of this study is to determine the life cycle environmental impacts of continuous electricity supply by energy systems which are expected to be independent from other networks in remote rural areas.

The scope of the study is from ‘cradle to grave’, with the system boundaries shown in Fig. 3. The life cycle stages considered comprise production of raw materials and infrastructure components, assembly of various parts, transportation, installation and operation of systems, and end-of-life management. The functional unit is defined as ‘generation and supply of 1 kWh of electricity’.

3.2.2. Inventory data

3.2.2.1. Raw materials processing, assembly and installation. The raw materials processing, assembly, and installation data have been sourced from the Ecoinvent 3.1 database [39] for the solar PV components, Li-ion batteries, system converter and distribution network using global market mixes. These have been adapted to correspond to the optimised sizes of the components obtained through HOMER modelling.
Manufacturing data for the other systems have been taken from literature. The literature data have been chosen based on data sources, age, and relevance (equipment size and purpose).

Specifically, data for micro-wind turbines have been obtained from Kabir et al. [22], for lead acid batteries from Spanos et al. [40] and the assembly data for diesel generators from Benton et al. [41].

Fig. 3. System boundaries for the energy systems considered in the study [PV: Photovoltaics; T: Transport; System credits; Micro-grid options only].

Table 2
Raw materials processing, assembly and installation data for 1 m² solar PV system [42].

| Life cycle stage | Amount |
|------------------|--------|
| Raw materials/components | |
| Photovoltaic panel, multi-Si wafer (m²) | 1 |
| Photovoltaic mounting system (m²) | 0.971 |
| Photovoltaic plant, electric components (pieces) | 0.043 |
| Installation | |
| Diesel, for ground mounted PV (MJ) | 1.743 |
| Electricity, low voltage, for ground mounted (MJ) | 0.029 |
| Electricity, low voltage, for roof mounted PV (MJ) | 0.156 |

Table 3
Raw materials and installation data for wind turbines.

| Life cycle stage | Capacity |
|------------------|----------|
| | 5 kW<sup>a</sup> | 100 kW<sup>b</sup> |
| Raw materials, moving parts<sup>c</sup> | |
| Aluminium, wrought alloy (kg) | 8.5 | 260 |
| Copper (kg) | 29.5 | 910 |
| Epoxy resin, liquid (kg) | 10 | – |
| Glass fibre (kg) | 18 | 1160 |
| Steel, low-alloyed, hot rolled (kg) | 234 | 4680 |
| Raw materials, fixed parts<sup>d</sup> | |
| Concrete, normal (m<sup>3</sup>) | 7.35 | 80.83 |
| Reinforcing steel (kg) | 75 | 9,100 |
| Steel, chromium steel 18/8 (kg) | 2058 | – |
| Steel, low-alloyed (kg) | – | 13,100 |
| Assembly and installation<sup>e</sup> | |
| Diesel (MJ) | 19.3 | 104.4 |
| Explosive, tovex (kg) | 3.8 | 20.6 |

<sup>a</sup> Household-scale installation.
<sup>b</sup> Community-scale installation.
<sup>c</sup> Kabir et al. [22].
<sup>d</sup> Greening and Azapagic [43].

Table 4
Raw materials, assembly and installation data for diesel generator.<sup>a</sup>

| Life cycle stage | Amount |
|------------------|--------|
| Raw materials<sup>b</sup> | |
| Aluminium alloy, AlMg<sub>3</sub> (kg) | 32.79 |
| Aluminium, cast alloy (kg) | 30.86 |
| Cast iron (kg) | 140.48 |
| Copper (kg) | 40.05 |
| Epoxy resin, liquid (kg) | 3.27 |
| Ferronickel, high-coal, 74.5% Mn (kg) | 6.05 |
| Lead (kg) | 0.73 |
| Molybdenum (kg) | 1.69 |
| Nickel, 99.5% (kg) | 2.66 |
| Pig iron (kg) | 179.29 |
| Printed wiring board (kg) | 1.45 |
| Silicon carbide (kg) | 146.69 |
| Steel, chromium steel 18/8 (kg) | 2.54 |
| Steel, low-alloyed (kg) | 498.28 |
| Steel, low-alloyed, hot rolled (kg) | 121.85 |
| Tin (kg) | 0.48 |
| Titanium (kg) | 0.36 |
| Zinc (kg) | 0.36 |
| Assembly and installation<sup>c</sup> | |
| Electricity (GJ) | 19.36 |
| Heat (GJ) | 65.34 |

<sup>a</sup> Installed capacity: 84 kW (based on the design in HOMER; see Section 4.1). Total weight of the generator: 1210 kg.
<sup>b</sup> Adapted from Benton et al. [41].
<sup>c</sup> Smith et al. [24].

Table 5
Raw materials, assembly and installation data per 1 kg of battery.<sup>a</sup>

| Life cycle stage | Battery type | Lead acid<sup>b</sup> | Li-ion<sup>b</sup> |
|------------------|--------------|----------------------|-----------------|
| Raw materials | | | |
| Cathode (kg) | 0.424 | 0.261 |
| Anode (kg) | 0.292 | 0.321 |
| Electrolyte (kg) | 0.171 | 0.143 |
| Separator (kg) | 0.025 | 0.043 |
| Electronics (kg) | 0.013 | 0.087 |
| Casing (kg) | 0.075 | 0.145 |
| Assembly and installation | | | |
| Electricity (MJ) | 4.59 | 0.691 |
| Heat (MJ) | 6.96 | – |

<sup>a</sup> Spanos et al. [40].
<sup>b</sup> Notter et al. [44].
all three studies have been sourced directly from manufacturers. Inventories for these assemblies are listed in Table S5 in Supporting Information (SI). Background life cycle inventory data are from Ecoinvent [39].

3.2.2.2. Transport. Components are assumed to be manufactured in China and transported to the island community by sea (Table 6). The exceptions to this are construction and installation components, including reinforcing steel and cement, which are assumed to be sourced locally.

3.2.2.3. Operation. The parameters used to determine the performance of each component in the hybrid systems can be found in Table S5 in the SI. Power output of the solar PV panels, wind turbines, and batteries has been calculated using the specifications in HOMER [14]. The lifetime of the batteries has also been determined through the HOMER simulations since the number of cycles, depth of discharge, and the lifetime of materials can be the limiting factor [40]. Maintenance of PV panels consumes 20 L/m² of water annually [42], while wind turbines use 0.04 kg of lubricating oil per kWh [45]. Emissions from the combustion of diesel have been sourced from Ecoinvent [39].

3.2.2.4. End-of-life waste management. At the end of their useful lifetime, the components of the energy systems have been assumed to be dismantled and recycled or landfilled. Ferrous metals, aluminium and copper are assumed to be recycled at rates of 39%, 47% and 44% respectively [46,47]. All other materials are landfilled. A closed loop recycling framework has been considered, wherein the recycled materials displace virgin materials in the assembly phase and any excess amount is credited against primary production. For the raw materials supply in China, the recycled fractions of steel, aluminium and copper are 10%, 19% and 34%, respectively [48,49].

3.2.3. Life cycle impact assessment

The LCA modelling and estimation of impacts have been carried out in GaBi ts 7.3 [50], using the ReCiPe 1.08 method [51]. Midpoint ReCiPe indicators have been selected because of their lower uncertainty and subjectivity than the end-point indicators [51]. A hierarchist perspective, the default model based on scientific consensus, has been used. This perspective can be interpreted as a balanced view between environmental manageability and the precautionary principle [52].

To streamline the discussion, the 18 midpoint indicators in the ReCiPe method are grouped into the following eight environmental issues:

- climate change: warming potential (GWP), excluding biogenic CO₂;
- air pollution: ozone depletion potential (ODP), photochemical oxidants formation potential (POFP), and particulate matter formation potential (PMFPP);
- water and soil pollution: freshwater and marine eutrophication potentials (FEP and MEP, respectively) and terrestrial acidification potential (TAP);
- ecotoxicity: freshwater, marine and terrestrial ecotoxicity potentials (FETP, METP and TETP, respectively);
- resource depletion: fossil, mineral and water depletion potentials

### Table 6

| Route                          | Distance (km) | Transportation mode          |
|-------------------------------|---------------|------------------------------|
| Factory to port               | 180           | Lorry, 3.5–7.5 t, EURO4      |
| International transport       | 2090          | Transoceanic freight ship    |
| Port to installation destination | 630          | Transoceanic freight ship    |

### Table 7

| System                      | Solar PV (kWp) | Wind turbine (kW) | Lead acid battery (kWh) | Lithium ion battery (kWh) | Battery life (yr) | Converter (kW) |
|-----------------------------|----------------|-------------------|-------------------------|--------------------------|------------------|----------------|
| H-PV + LA                   | 2.89           | –                 | 21                      | –                        | 11.2             | 1.8            |
| H-PV + LI                   | 3.45           | –                 | –                       | 10                       | 15               | 1.4            |
| H-WT + LA                   | –              | 10⁻⁶             | 37                      | –                        | 16.7             | 2.4            |
| H-WT + LI                   | –              | 10⁻⁶             | –                       | 22                       | 15               | 2.2            |
| H-PV + WT + LA              | 1.29           | 5                 | 10                      | –                        | 10.6             | 0.9            |
| H-PV + WT + LI              | 1.29           | 5                 | –                       | 6                        | 15               | 1.4            |

- H: household-scale; PV: solar photovoltaics; WT: wind turbine; LA: lead acid battery; LI: Li-ion battery.
- Total battery bank capacity.
- Two wind turbines with 5 kW each.

4. Results and discussion

4.1. System design and component sizing

The results of the design and component sizing for the household and community scale systems are detailed in Table 7 and Table 8, respectively. In total, six different configurations have been found feasible for the household and 15 for the community hybrid systems. All the configurations are optimised to be energy self-sufficient. This is discussed further below.

4.1.1. Household-scale systems

As mentioned earlier, for a single household with a daily electricity demand of 8.22 kWh (3000 kWh/yr), diesel generators are not suitable for continuous daily use due to their much larger size. Hence, only solar PV and micro-wind turbines are applicable for stand-alone installations at the household level. Combined with battery storage, they are capable of meeting fully the household electricity needs. In the hybrid systems, combining the wind turbine and solar PV, the former provides 77% of the household load and the latter the remaining 23%, based on the simulations in HOMER (see Fig. S1 in the SI).

Among the multiple size combinations that are viable, the designs chosen for further analysis are those with the smallest feasible sizes. As shown in Table 7, depending on the system configuration, the installed capacity of solar PV ranges from 1.29 to 3.45 kWp, with total annual operating hours of 4380 hr and a capacity factor of 17.9%. The capacity of micro-wind turbines is fixed at 5 kW in all the designs and it generates power for 6860 h/yr, yielding a capacity factor of 15.7%. The capacity of the lead acid battery is higher (10–37 kWh) than that of the lithium-ion equivalent (6–22 kWh), but the latter lasts longer (Table 7).

An one-week snapshot of the generation, consumption, and storage profile of a household-scale system is shown in Fig. 4. This provides an insight into the operational challenges associated with hourly and daily variation in generation and consumption as the peaks in electrical load are not consistently coincident with the peaks in the output from PV and wind turbine. Furthermore, periods of low or no PV output have significant overlaps with periods of similar wind performance. Hence, the battery provides an essential service in matching generation and consumption throughout the day. Most of the energy stored by the
battery is wind power; hence, periods of low output from the wind turbine can result in significant reliance on the battery as the energy source.

4.1.2. Community-scale systems

As with the household systems, the chosen designs of community micro-grid systems are comprised of the smallest feasible components. For the community of 50 households (411 kWh/day), the PV capacities range widely (26.9–187.4 kWp) across the 15 system configurations (Table 8). A similarly wide variation in the capacity is also found for the batteries (217–1514 kWh for lead acid and 117–448 kWh for Li-ion). In consideration of land occupation and energy payback, the 100-kW wind turbine is preferred over the equivalent multiple number of the smaller turbines [22].

The PV panels operate with the same performance as for the household scale, but the taller 100-kW wind turbines can operate for 7909 h/yr to achieve a capacity factor of 19.3%. A stand-alone diesel generator has a mean electrical efficiency of 27.6%, but addition of a battery can increase its efficiency up to 32.4%. This results from fewer hours of operation, but at higher power outputs.

A sample weekly electrical profile of a hybrid option is presented in Fig. 5. The diesel generator is operated primarily as a peak power source. The simulation has also optimised the scheduling such that the generator operates near maximum efficiency and excess electricity can be stored by the battery. As with the single household profile (Fig. 4), dips in PV and wind output are managed by discharging the energy stored in the batteries.

4.2. Life cycle environmental impacts

This section discusses first the impacts of the household-scale systems, considering both individual technologies (solar PV and wind) and their combinations detailed in Section 4.1.1. This is followed by an equivalent discussion for the community-scale systems and finally by their comparison with the household systems in Section 4.2.3.

4.2.1. Household-scale systems

Fig. 6 compares the environmental impacts of the six system configurations. The data is presented in Table 8.

Table 8

| System | Solar PV (kWp) | Wind turbines (kW) | Diesel generator (kW) | Diesel (kg/yr) | Diesel generator use (hr/yr) | Lead acid battery (kWh) | Lithium ion battery (kWh) | Battery life (yr) | Converter (kW) |
|--------|---------------|--------------------|-----------------------|----------------|-----------------------------|-------------------------|-------------------------|-----------------|---------------|
| C-DG   | –             | –                  | 84                    | 62,192         | 8760                        | –                       | –                       | –               | –             |
| C-DG + LA | –           | –                  | 84                    | 45,022         | 4804                        | 138                     | 3                       | 17.6            | 12.5          |
| C-DG + LI | –            | –                  | 84                    | 42,445         | 3758                        | –                       | 171                     | 12.5            | 20.9          |
| C-PV + LA | 137.9      | –                  | –                     | –              | –                           | 1144                    | –                       | –               | –             |
| C-PV + LI | 187.4     | –                  | –                     | –              | –                           | –                       | 448                     | 15              | 69.8          |
| C-WT + LA | –          | 300\(^c\)           | –                     | –              | –                           | 1514                    | –                       | 16.7            | 76.7          |
| C-WT + LI | –          | 500\(^d\)           | –                     | –              | –                           | –                       | 354                     | 15              | 63.0          |
| C-DG + PV + LA | 81.3 | –                  | 84                    | 14,726         | 1754                        | 390                     | –                       | 7               | 33.5          |
| C-DG + PV + LI | 69.7       | –                  | 84                    | 16,318         | 1067                        | –                       | 262                     | 15              | 36.2          |
| C-DG + WT + LA | –         | 100                 | 84                    | 16,016         | 2194                        | 217                     | –                       | 6.95            | 31.2          |
| C-DG + WT + LI | –         | 100                 | 84                    | 14,937         | 917                         | –                       | 151                     | 10.3            | 45.5          |
| C-PV + WT + LA | 64.7      | 100                 | –                     | –              | –                           | 534                     | –                       | 10.8            | 61.6          |
| C-PV + WT + LI | 137.0     | 100                 | –                     | –              | –                           | 420                     | –                       | 15              | 76.7          |
| C-DG + PV + WT + LA | 52.5 | 100                 | 84                    | 6668           | 818                         | 253                     | –                       | 7.7             | 33.5          |
| C-DG + PV + WT + LI | 26.9     | 100                 | 84                    | 11,192         | 835                         | –                       | 117                     | 12.1            | 36.3          |

\(^a\) C: community-scale; DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid battery; LI: Li-ion battery.

\(^b\) Total battery bank capacity.

\(^c\) Three wind turbines with 100 kW each.

\(^d\) Five wind turbines with 100 kW each.

Fig. 4. An example weekly household electrical profile (H-PV + WT + LI) [H: household; PV: photovoltaics; WT: wind turbine; LI: lithium-ion battery].

Fig. 5. A sample weekly electrical profile of a hybrid option (C-DG + PV + LA) [C: community-scale; DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid battery].
configurations considered at the household level. As can be seen, the hybrid installations combining rooftop PV and Li-ion batteries (H-PV + LI) have the lowest impacts in 12 categories, while wind turbines with lead-acid batteries (H-WT + LA) are the worst option for 14 impacts. The majority of impacts in the stand-alone solar PV systems are due to the PV itself; similarly, the impacts in the wind-turbine based systems are mainly due to the turbines. In both stand-alone systems, the contribution of batteries is comparatively higher than in hybrid options. In the latter, wind turbines cause the majority of the impacts.

The contribution analysis for the stand-alone PV system (see Fig. S2 in the SI) shows that the production of polycrystalline Si cells contributes more than half to the total impacts from the PV system in most impact categories. These arise due to emissions from the material processing stages and are proportional to the fossil fuels consumed in this stage [53]. For FEP, MDP and HTP, the production of electric components is another significant source of impacts (> 28%). This is due to the copper content and the associated air emissions of SO₂, trace elements, and dust in its life cycle (mining, beneficiation, and winning).

![Graph showing electrical generation/load (kW) and state of charge (%).](image)

Fig. 5. An example weekly electrical profile of a community with 50 households (C-DG + PV + WT + LI) [C: community; DG: diesel generator; PV: photovoltaics; WT: wind turbine; LI: lithium-ion battery].

![Graph showing life cycle environmental impacts.](image)

Fig. 6. Life cycle environmental impacts of household-scale (H) power systems considering stand-alone and hybrid systems, comprising differing combinations of solar photovoltaics (PV), wind turbines (WT), lead acid (LA) and lithium (LI) batteries. [Impacts expressed per kWh of total electricity supplied. In the hybrid systems, contribution of batteries is comparatively higher than in hybrid options. In the latter, wind turbines cause the majority of the impacts.]

7
environmental issues, are discussed below.

For all other categories, the contribution of stainless steel alone wind turbine systems have on average 60% higher impacts than to the contribution of the energy storage components since previous lifetime of Li-ion batteries lead to lower consumption of materials and energy compared to lead acid batteries, but the different chemistries also result in different impacts for each component. For instance, copper in the graphite anode for Li-ion batteries contributes significantly to eutrophication and ecotoxicity, whereas the lead anode in the lead acid battery is mostly recycled and has relatively lower impacts.

The following sections discuss the findings in more detail for each impact category, starting with the stand-alone power systems and followed by their hybrid configurations. A particularly attention is given to eutrophication and ecotoxicity, whereas the lead anode in the lead acid battery is mostly recycled and has relatively lower impacts.

Between the two types of battery investigated, systems with a Li-ion battery have lower impacts than those with a lead acid battery in most categories, except eutrophication (FEP and MEP), and human and terrestrial toxicities (HTP and TETP); see Fig. 6. The higher efficiency and lifetime of Li-ion batteries lead to lower consumption of materials and energy compared to lead acid batteries, but the different chemistries also result in different impacts for each component. For instance, copper in the graphite anode for Li-ion batteries contributes significantly to eutrophication and ecotoxicity, whereas the lead anode in the lead acid battery is mostly recycled and has relatively lower impacts.

The lead acid battery is a relatively minor source of PMFP (12%) and POFP (15%) in the H-WT + LA system, but it contributes more significantly to ODP (28%). By contrast, the Li-ion battery in the H-WT + LI system contributes < 11% in these categories. The fixed parts cause essentially all of the remaining ODP in both wind systems due to halon emissions (1301 and 1211), associated with use of crude oil and natural gas in production of steel and concrete [55]. Steel production is also the most significant source of PMFP due to emissions of dust, NOx, and SOx. It also causes POFP because of the associated NOx, SO2, and other NMVOC emissions.

Water and soil pollution (FEP, MEP, TAP): As mentioned previously, FEP and MEP are two categories where Li-ion batteries perform worse than lead acid batteries. Thus, H-PV + LA has the lowest FEP and MEP and H-WT + LI the highest. Phosphate emissions to water associated with lead and copper refining add to the freshwater eutrophication potential (FEP) of the PV system (33% for lead acid, 36% for Li-ion). Nitrate discharge to water and NOx emissions from lead acid batteries and PV cell production are the main sources of marine eutrophication (MEP). Credits for recycling lead provide substantial reductions in eutrophication (53% and 34% of the battery’s FEP and MEP, respectively). Similar to PMFP, SO2 emissions are the source of the majority of terrestrial acidification potential (TAP): 52% from the battery in the H-PV + LA system and 58% from the PV panels in the H-PV + LI system. Finally, significant SO2 emissions from the remelting process for lead acid battery recycling are responsible for 20% of the life cycle TAP.

For the wind system with the lead acid battery, the latter contributes 15% of the total FEP and MEP and 22% of TAP. For the equivalent system with the Li-ion battery, the latter contributes significantly to FEP (29%) due to phosphates discharged to water. For both systems, > 40% of eutrophication and acidification are derived from stainless steel production. Phosphates, nitrates and NOx emissions drive eutrophication, while TAP is mostly from SO2 emissions.

Ecotoxicity (FETP, METP, TETP): Terrestrial ecotoxicity is another category where the options with Li-ion batteries have higher impacts than those with lead acid counterparts. This in turn leads to H-PV + LI being the worst option for TETP and H-PV + LA the best among the four stand-alone systems. Copper discharge to water and air is the main source of ecotoxicity. In the PV systems, these are mostly attributed to the solar PV panel production, although the lead acid battery also add 8–32% to the total ecotoxicity potential of a PV-based system. The end-of-life management of the solar PV system has considerable water ecotoxicity impacts due to copper emissions during the remelting of scrap aluminium.

More than half of the ecotoxicity impacts of the wind systems derive from the discharge of nickel and zinc to water and copper to air in the production chain of stainless steel. The battery adds no more than 17% and 13% of the impacts for a lead acid and Li-ion based systems, respectively.

Resource depletion (FDP, MPFP, POFP): Similar comparisons for the household-scale PV systems are seen in air pollution categories. Ozone depletion potential (ODP) is estimated to be 23 and 19 µg CFC-11 eq./kWh for H-PV + LA and H-PV + LI systems, respectively. Notable hotspots are the use of sodium hydroxide in lead acid battery recycling (which has associated emissions of CCl4) and refrigerants (R-22 and R-12) in the solar PV panel production. For particular matter formation (PMFP), 49% of the impact in the H-PV + LA system originates from battery production, primarily as SO2 emissions. On the other hand, the Li-ion battery cell is a relatively minor contributor (20%) to PMFP in the H-PV + LI system. Nitrogen oxides from the production of the solar PV panel are the dominant cause of POFP in the solar PV-based systems.

The lead acid battery production in the H-PV + LA system is a major source of POFP (42%), second only to the PV panels (46%).

The lead acid battery is a relatively minor source of PMFP (12%) and POFP (15%) in the H-WT + LA system, but it contributes more significantly to ODP (28%). By contrast, the Li-ion battery in the H-WT + LI system contributes < 11% in these categories. The fixed parts cause essentially all of the remaining ODP in both wind systems due to halon emissions (1301 and 1211), associated with use of crude oil and natural gas in production of steel and concrete [55]. Steel production is also the most significant source of PMFP due to emissions of dust, NOx, and SOx. It also causes POFP because of the associated NOx, SO2, and other NMVOC emissions.

In the stand-alone PV systems, the household-scale PV system with lead acid batteries (H-PV + LA) emits 131 g CO2 eq./kWh over its life cycle compared to 105 g CO2 eq./kWh from the system with Li-ion batteries (H-PV + LI) (Fig. 6). For the H-PV + LA system, 40% of the impact is attributed to the battery, primarily from the energy used for the refining and treatment of lead. On the other hand, in the lithium battery system (H-PV + LI), the battery is responsible for only 12% of the GWP. In both systems, the most significant source of GHG emissions is fossil fuel energy used for the assembly of solar panels (> 50%).

The life cycle GHG emissions of the wind stand-alone systems amount to 470 g CO2 eq./kWh if a lead acid battery is used (H-WT + LA), and 440 g CO2 eq./kWh with a Li-ion battery (H-WT + LI). The battery is responsible for 13% and 6% of the climate change impacts, respectively. For both systems, the GHG hotspot is the fixed parts (> 86%), with stainless steel production contributing up to 70% of the emissions.

Air pollution (ODP, MPFP, POFP): Similar comparisons for the household-scale PV systems are seen in air pollution categories. Ozone depletion potential (ODP) is estimated to be 23 and 19 µg CFC-11 eq./kWh for H-PV + LA and H-PV + LI systems, respectively. Notable hotspots are the use of sodium hydroxide in lead acid battery recycling (which has associated emissions of CCl4) and refrigerants (R-22 and R-12) in the solar PV panel production. For particular matter formation (PMFP), 49% of the impact in the H-PV + LA system originates from the production of the PV panels (84–95%).
The battery component of the H-WT + LA system is responsible for 17% of FDP and 23% of MDP. On the other hand, the Li-ion battery in the H-WT + LI system contributes only 8% in the same categories. Water depletion from both types of batteries is considered small (<5%). The fixed parts are the largest contributors to resource depletion (>76%), mainly due to coal, which is used as a raw material in steel as well as an energy source. Notable materials which impact on mineral resource depletion are chromium and nickel (in stainless steel), and tin and lead (in lead acid battery).

**Land use (ALOP, NLTP, ULOP):** Land occupation and transformation in the life cycle of the PV systems range from 0.04 to 19.7 m² over the 25-year lifetime. The H-PV + LA system has an agricultural land occupation potential (ALOP) of 68 cm²a, an urban land occupation (ULOP) of 16 cm²a, and natural land transformation (NLTP) of 20 mm², all values per kWh of electricity generated. In total, 64% of ALOP and 39% of NLTP result from occupation of forested lands for the extraction of lead and silicon. In comparison, the life cycle of a Li-ion battery in the H-PV + LI system contributes 10–22% of the system's land use.

Land occupation of the H-WT + LA system amounts to 96.1 and 36.4 m² of agricultural and urban land, respectively, during its 25-year life. Around 32% of NLTP can be attributed to lead extraction. In contrast, majority of the land use impacts of the WT + LIB system (77% of ALOP and 49% of ULOP) are from the fixed parts, to some extent due to the mass of these components relative to the rest of the system. Transformation and occupation of natural land is driven by material extraction for concrete and steel; hence, the credits for recycled steel provide 28–32% reductions in the impacts of steel consumption.

**Human health (HTP, IRP):** The battery components are significant contributors to human toxicity potential (HTP), causing 38% of 217 g 1,4-DB eq./kWh for H-PV + LA and 33% of 229 g 1,4-DB eq./kWh for H-PV + LI. This is due to discharge of manganese, zinc, and other metals to water. Production of lead and graphite is the hotspot for the batteries, but recycling reduces their life cycle HTP by more than 20%. Ionizing radiation potential (IRP) comes from Rn-222 and C-14 emissions to air. These are linked to energy use (electricity, oil and gas) in the production of solar panels and batteries.

In the wind systems, lead acid batteries contribute around 18% to HTP and IRP while Li-ion batteries have a greater influence on human toxicity (27%) but a lower contribution to IRP (9%). The HTP from the Li-ion battery is primarily attributed to emissions of heavy metals to water from the production of the graphite anode. In terms of material components, stainless steel is a significant source of HTP (42%) in both the production and recycling process due to associated discharge of Zn and Mn to water. However, credits from recycling reduce the impact by a fifth. Finally, as for the PV-based systems, ionising radiation is due to Rn-222 and C-14 emitted in the life cycle of electricity used in the production of battery cells and steel.

**4.2.1.2. Hybrid household-scale systems.** While the hybrid systems have lower impacts than the stand-alone wind options per kWh delivered, they are environmentally worse than the PV-based systems (Fig. 6). On the one hand, the addition of solar PV panels to a wind system reduces the number of turbines and batteries required. Because the solar PV components which replace the wind turbines in the hybrid designs have lower impacts, a net reduction is observed across all categories compared to the stand-alone wind systems. Conversely, if PV systems were reduced in capacity and compensated with a wind turbine, the higher impacts from the latter overcome the environmental savings from the smaller size of solar PV. The exceptions to this trend are TETP and NLTP, where a hybrid option has the lowest impacts among the six household-scale systems. However, the differences are small and subject to uncertainty. Among the different components in the hybrid system, the wind turbine dominates in all impact categories with contributions of 50–93% (Fig. 6).

**4.2.2. Community-scale micro-grid systems**

For the 15 options for a community micro-grid, seven are single-source systems and eight are hybrid energy systems with multiple generation sources (Table 8). The LCA results for single-source are discussed in the next section, followed by a discussion on the hybrid micro-grid systems in Section 4.2.2.1.

**4.2.2.1. Single-source micro-grid systems.** As observed in Fig. 8, diesel generators (DG), the baseline technology, perform the worst in climate change (GWP) and air pollution (ODP, PMFP, and POFP). This is due to the emissions of CO₂, CO, SOₓ and NOₓ during diesel combustion. Diesel generators also have the highest fossil depletion, agricultural land occupation and ionising radiation, related to the diesel production chain, specifically extraction of crude oil and C-14 emissions from drilling.

Adding lead acid or lithium batteries to the diesel generator allows a more efficient operation by decoupling the electricity load and generation rate. As a result, the generator operates only half of the year and consumes 30% less fuel. In terms of environmental impacts, Li-ion batteries reduce the impacts on average by 30% while lead acid batteries only achieve a 20% reduction per kWh. However, addition of the Li-ion battery leads to the MDP more than twice as high as that of the diesel generator without a battery due to the need to replace the latter every three years. In contrast, the C-DG + LI system has one of the lowest impacts in six categories (FEP, FETP, METP, MDP, WDP, and HTP) among the micro-grid options. This is in part due to the reduced fuel use and higher efficiency associated with the Li-ion battery, but also due to the environmental advantages of diesel generators in these categories against solar PV panels and wind turbines.

The C-PV + LI system has the highest impacts in five categories (FETP, METP, TETP, ULOP and WDP) among the single-source micro-grid options – up to 18 times higher than those of the diesel generator (DG). As discussed in a previous section, processing of metals (notably silicon and copper) for the PV panels and electric installation contribute significantly to most of these impact categories. The high ULOP is due to the land occupied by the PV system during its lifetime. However, C-PV + LI has the lowest GWP, PMFP, POFP, TAP, and FDP than any other single-source micro-grid option.

The wind micro-grid options (C-WT + LA and C-WT + LI) have the highest FEP, MDP and HTP, mostly attributed to the copper and steel used for the 100-kW wind turbines. While wind turbines perform worst in three categories, they have lower ODP, TETP, ALOP, NLTP, and IRP than diesel generators and solar PV systems. This is in contrast with the comparison of the household-scale wind turbine (5 kW) and the PV systems (see Section 4.2.1). Further discussion on the effect of scale on
Fig. 7. Comparison of life cycle environmental impacts of stand-alone and hybrid systems at the household scale. [Basis: 77% of electricity is from wind and 23% from solar PV, with either lead-acid (LA) or Li-ion (LI) battery. Stand-alone systems operate with separate controllers and storage systems while the hybrid systems are sized to operate with shared system components. For impacts nomenclature, see Fig. 6.]

Fig. 8. Life cycle environmental impacts of community-scale micro-grid options utilising a single source of electricity and battery storage [Impacts expressed per kWh of electricity supplied. Some impacts have been scaled to fit; to obtain the original values, multiply by the factors given on the x-axis in brackets. DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid; LI: Li-ion. For impacts nomenclature, see Fig. 6.]
the environmental impacts of micro-wind turbines is presented in Section 4.2.3.

Therefore, these results suggest that no energy source completely dominates the others across the 18 impact categories. If all impact categories have equal importance, the diesel generator would be the worst option as it has the highest impacts in 11 categories. In that case, the wind micro-grid with lead acid batteries (C-WT + LA) would be considered the best option as it has relatively low impacts in all categories, except metal depletion. The alternative C-WT + Li option has the highest FEP and HTP, while both PV options have the highest FETP and METP among the seven designs.

4.2.2.2. Hybrid micro-grid systems. In the community-scale hybrid micro-grid systems, detailed in Table 8, wind turbines provide on average 64% of the load (see Fig. S1 in the Supporting Information). The high renewable fraction also indicates that diesel is only used as a backup source when solar and/or wind resources are low. Furthermore, integration of renewable energy reduces fuel consumption by 62–85% relative to the diesel generators with batteries. The feasibility of a system without a diesel generator as backup also confirms that tropical islands, as considered in this study, are prime candidates for a fully renewable-powered micro-grid system.

In terms of life cycle environmental impacts, hybridisation of energy systems can result in synergistic improvements as seen in the hybrid PV-wind system with lead acid batteries (C-PV + WT + LA). Here, the per-kWh impacts are 8–52% lower in 10 categories (Fig. 9) than for the individual C-PV + LA and C-WT + LA systems (Fig. 8). This is achieved by significant reductions in the size of components as the hybrid system requires only half the PV size and a third of the wind turbines for the same function. As a result, the hybrid system that integrates PV, wind turbines and lead acid batteries (C-PV + WT + LA) has the lowest impacts in 10 categories (GWP, ODP, PMFP, POFP, MEP, TAP, FDP, ALOP, NLTP and IRP) among the 15 micro-grid options (single-source and hybrid).

Even for retrofit cases using existing diesel generator, addition of renewable energy sources and batteries improves environmental performance in many categories. Notable exceptions are MDP and WDP, where the savings from reduced use of diesel generator cannot compensate the impact of the added components. Only for the C-DG + PV + Li system (Fig. 9) are all the impacts lower than for the C-DG system (Fig. 8). Despite the added contribution of the solar PV system and Li-ion battery to the system, the reduced use (and, consequently, lower fuel consumption and longer life) of the generator overcomes the additional impacts.

Another notable option is the C-DG + WT + Li system whose eco-toxicity impacts (FETP, METP, TETP) and land occupation (ALOP, ULOP) are among the lowest. While wind turbines have a relatively high FETP and METP (proportional to steel content) and diesel fuel contributes significantly to ALOP and TETP, the hybridised system utilises less of each component and lowers the overall impact in these categories. Since the land occupied by ground-mounted solar PV panels is categorised as urban land, the absence of PV components in this system explains the low ULOP.

The trade-offs between generation capacity and storage capacity, and their effects on environmental performance, are seen most prominently in the comparison of the hybrid PV-wind designs (C-PV + WT + LA and C-PV + WT + Li). Because the optimisation in HOMER considers relative costs between components (wherein lead acid batteries are 57% cheaper than Li-ion batteries per kWh capacity), the resulting design of the C-PV + WT + Li system has lower storage capacity but larger PV capacity to match the load profile. Hence, due to the lower impacts of Li-ion batteries in most categories (as discussed in Section 4.2.1), the intuitive expectation is that the C-PV + WT + Li option would have lower impacts than the C-PV + WT + LA option. However, for almost all categories, the C-PV + WT + LA system has lower impacts than C-PV + WT + Li (Fig. 9). Contribution analysis (Fig. S4 in the SI) reveals that, while the impacts from the battery are indeed lower for the option with Li-ion batteries, this system has a larger PV size. The lower environmental impacts resulting from shifting to Li-ion batteries is overcome by the impacts of more PV components.

Fig. 9. Life cycle environmental impacts of community-scale hybrid micro-grid options [Impacts expressed per kWh of electricity supplied. Some impacts have been scaled to fit; to obtain the original values, multiply by the factors given on the x-axis in brackets. DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid; Li: Li-ion. For impacts nomenclature, see Fig. 6.]
required to match the lower storage capacity.

Similar to the single-source micro-grid options, no hybrid micro-grid design dominates in all environmental categories. Assuming equal importance of all the impacts, C-PV + WT + LA can be considered the best option with seven impacts lower than for the other hybrid systems. As mentioned earlier, this system is also the best alternative for 10 categories than any other single-source or hybrid option. Hence, overall, it could be selected as environmentally most sustainable system.

4.2.3. Comparison of household and community-scale systems

This section discusses the environmental implications of distribution and installation scale for the deployment of solar PV and wind turbine technologies. To facilitate the comparisons, impacts of solar PV, wind, and hybrid PV + wind systems are considered with corresponding contributions of each component to the total impacts.

The obvious difference between household- and community-scale systems is the requirement for a distribution network in the micro-grid options. As shown in Figs. 10–12, the distribution network contributes 16–22% of ALOP, 15–30% of FEP, 15–29% of HTP, 13–21% of MEP, 6–25% of MDP and 9–31% of TETP of the different micro-grid systems proposed. It has less influence (< 10%) in other impact categories. Most of the impacts of the distribution network are derived from copper use (84% of its FEP, 85% of HTP, 91% of MEP, 47% of MDP, 35% of TETP). Wood used for the utility poles are the main source of ALOP (65%). Salts used to preserve the wood are reported to leach out during its lifetime [56], contributing 58% of the TETP of the distribution network.

Comparing the household-scale PV system and solar PV micro-grid (Fig. 10), higher impacts are seen for the micro-grid options. Aside from the additional impacts from the distribution network, the ground mounting for the small-scale solar PV farm has higher impacts than the roof-mounting of household-scale PV systems. This is mainly due to the higher requirement of materials per unit area for ground mounting. Most notably, ULOP is 26 times higher in the community-scale PV + LA system than the equivalent household-scale system, and 44 times higher for the PV + Li system against the household PV + Li option. Overall, for all the impact categories but ULOP, an average increase of 15% is observed when the solar PV systems are scaled up to the community level. However, the per-kWh impacts of the PV + battery system are practically the same for both scales due to the modular structure of these components (i.e. their number increases linearly with the electricity demand).

As previously suggested in literature, the environmental performance of wind turbines follows a principle similar to the “economies of scale” [22,43]. The same is seen in this study as the impacts of the micro-grid designs using 100-kW wind turbines are 21–92% lower than of the household-scale wind systems with 5-kW turbines (Fig. 11). The most significant source of impact reduction is the use of low-alloyed steel instead of stainless steel for the fixed parts of the wind turbine. Another factor is the higher utilisation, measured via the capacity factor, of the larger turbine (19%) compared to the smaller one (16%). This also translates into lower requirements for energy storage and hence the smaller battery. In terms of environmental impacts, there is an average reduction of 19% and 68% in the contributions from the lead acid and Li-ion batteries, respectively, across all impact categories.

The effect of scaling up to hybrid PV + wind systems does not follow a single trend since the impacts of wind turbines decrease and those of the solar PV systems increase when deployed in larger installations. For most categories, the hybrid micro-grid option has lower impacts than the hybrid home systems (Fig. 12). Only for ULOP is the opposite true due to the high contribution of ground mounting for the PV panels. Interestingly, for the hybrid PV + wind options using Li-ion batteries, the FEP, HTP and TETP of both household- and community-scale designs are almost identical. The lower impacts from the larger wind turbine are counteracted by the increased impacts of the solar PV component and the distribution network. As previously discussed, these categories are where the hotspots of the distribution network are most evident.

![Fig. 10. Comparison of life cycle impacts of household and community-scale solar PV systems with battery storage. [Impacts expressed per kWh of electricity supplied. Some impacts have been scaled to fit; to obtain the original values, multiply by the factors given on the x-axis in brackets. H: household; C-community; DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid; LI: Li-ion. For impacts nomenclature, see Fig. 6.]](image-url)
Fig. 11. Comparison of life cycle impacts of household and community-scale wind turbine systems with battery storage. [Impacts expressed per kWh of electricity supplied. Some impacts have been scaled to fit; to obtain the original values, multiply by the factors given on the x-axis in brackets. H: household; C: community; DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid; LI: Li-ion. For impacts nomenclature, see Fig. 6.]

Fig. 12. Comparison of life cycle impacts of household and community-scale hybrid solar-wind systems with battery storage. [Impacts expressed per kWh of electricity supplied. Basis: see Table 7 and Table 8. Some impacts have been scaled to fit; to obtain the original values, multiply by the factors given on the x-axis in brackets. H: household; C: community; DG: diesel generator; PV: solar photovoltaics; WT: wind turbine; LA: lead acid; LI: Li-ion. For impacts nomenclature, see Fig. 6.]
In summary, this analysis suggests that the effects of installation size on solar PV systems and micro-wind turbines are greatly influenced by the choice of materials of the structural components, i.e. the mounting of PV panels and the tower of wind turbines. For the battery, the attributed environmental impacts per kWh delivered are found to be dependent on the efficiency of the generation source and not directly on the installed capacity of the system. This is seen when comparing the household and community-scale solar PV systems (Fig. 10) where the efficiency of the PV panels is the same for both, and the impacts of the battery are relatively unchanged by scale. In comparison, the wind power systems (Fig. 11) where the larger turbine has a higher capacity factor than the smaller installation has lower impacts of battery storage per kWh delivered.

4.2.4. Comparison of results with literature

As noted in the literature review section, previous LCA studies investigated the environmental impacts of solar PV and wind systems in off-grid conditions. However, most of these focused on GHG emissions and related GWP, with only a few extending the analysis to other categories, notably acidification, eutrophication and photochemical oxidants formation [57]. Comparisons between different studies are difficult due to different systems considered, their geographical locations, size, assumptions, data, and life cycle impact assessment methods used. Furthermore, there are no previous studies which considered as comprehensive suite of designs at different scales as in the current work. For this reason, it has only been possible to compare the results from this study with a limited number of other publications. These comparisons are shown in Fig. 13 and Fig. 14, with the former related to PV systems and the latter to wind turbines, both with or without battery storage.

The studies on solar PV systems shown in Fig. 13 include those by Bilich et al. [25] carried out for a PV micro-grid in Kenya, by Stamford [58] for different configurations of roof-mounted PV installations in the UK, and by Uctug and Azapagic [59] for a PV-Li-ion battery system in Turkey. A range of results for GWP and some other impacts, as reviewed by Kommalapati et al. [20] and Asdrubali et al. [57], is also included.

As can be seen in Fig. 13, the results vary across the studies. The main source of the difference is the functional unit: 1 kWh of electricity produced ([20,58,59]) vs 1 kWh of electricity consumed ([25] and this study). The difference in definition is subtle, but the implications are significant since solar energy has variable generation. This explains the fact that the results of Bilich et al. [25] and of this study are quite similar as both studies are based on the same functional unit and system architecture. The significantly higher TETP reported by Stamford [58] is primarily attributed to chromium emissions during the production of stainless steel for PV mounting. In comparison, this study utilises reinforcing steel and aluminium which have lower TETP per mass than stainless steel. Other sources of variance include location-specific data, such as insolation, PV efficiency and the system’s lifetime [57]. However, in general, the results of the current study are within the range of those reported in the literature.

For small-scale wind turbines (Fig. 14), one of the few papers that includes a battery with a micro-wind turbine is that by Glassbrook et al. [60]; however, the authors only considered GHG emissions and embodied energy. Other references for comparison are limited to the micro-wind turbine alone and are based in Canada [22] and the UK [43]. The results for GWP and TAP reported by Asdrubali et al. [57] in their review are also included in the comparison. The functional unit in all these studies is 1 kWh of electricity generated; for comparability, the results in this study have been converted to the same functional unit (using the factors 4.8 and 3.5 for the H-WT + LA and C-WT + LA systems, respectively).

Fig. 14 indicates that the impacts estimated in this study are of the same order of magnitude as the literature values but they tend to be
higher due to the inclusion of energy storage and distribution (for the community-scale options). However, higher toxicity impacts (FETP, HTP, TETP) were reported by Greening and Azapagic [43]. This is attributed to the higher amount of steel in their system (25.4 vs 19.9 t here). The other sources of variance include turbine efficiency, wind speed, and the system’s lifetime [57,60].

5. Conclusions

This study has designed and evaluated the environmental sustainability of 21 system configurations for electrification of off-grid rural communities. Six of the design options are suitable for installations in individual households and the rest for integration into a community micro-grid. The hybrid micro-grid system with solar PV, wind turbine, and lead acid battery (C-PV + WT + LA) has the lowest impacts in most of the 18 categories considered. The worst options are the household-scale wind turbine with lead acid battery (H-WT + LA) and the community diesel generator (C-DG) which have the highest impacts in six and eight categories, respectively.

Stand-alone and hybrid systems are feasible at both household and community scales even without a diesel generator as backup. Batteries are essential in improving the reliability of solar and wind power, allowing renewable fractions of up to 100%. Energy storage systems also improve the operation of diesel generators by reducing the required operating hours by 50% and fuel consumption by 30%. However, they contribute to the impacts significantly, especially mineral resource depletion (up to 88% in home systems and 78% in micro-grid systems). Comparing the energy storage options alone, Li-ion batteries have lower environmental impacts in most categories than lead acid batteries per kWh capacity. Comparing the three generation technologies, solar PV (household or community-scale) has the lowest climate change impact and depletion of fossil resources, while community-scale wind turbines have the lowest land use and terrestrial ecotoxicity. Diesel generators are the best option for water ecotoxicity, metal and water depletion among the community-scale electricity-generating options.

Hybridisation, i.e. the use of multiple technologies as an integrated power system, is found to reduce the environmental impacts of off-grid electricity by up to 40% per kWh relative to an equivalent electricity mix from separate installations. This synergistic effect is most prominent in hybrid solar PV and wind systems as their hourly generation profiles can complement each other, leading to up to 70% lower requirements for energy storage. Diesel generators also benefit from hybridisation with renewable energy and batteries. By allowing operation at higher efficiencies for shorter hours through optimised dispatch, fuel consumption is reduced by > 62%, resulting in lower environmental impacts. However, the installation of more components also leads to higher resource depletion.

The environmental implications of installing solar PV and wind energy systems in individual households compared to a centralised community micro-grid have also been analysed. While the modularity of solar PV panels means practically constant impacts per functional unit across scales, the different mounting types and the distribution network increase most impacts of the community-scale solar PV systems on average by 15% and land occupation by 26–44 times. In contrast, higher efficiency and lower quantity of materials per kWh capacity of larger wind turbines lead to environmentally more sustainable utilisation of wind power in micro-grids, despite the additional distribution infrastructure. Based on these results, an interesting future study would be the investigation of combined designs of household-scale PV systems and wind micro-grids which have the lowest environmental impacts among the options considered.

The results of this study complement the techno-economic analyses of home and community energy systems in literature. While the current study focuses on solar and wind resources, the framework presented here can be applied to other forms of renewable energy, such as hydropower and biomass in future studies. The results can also be refined to suit specific scenarios by modifying the load and resource profiles. These can be used to inform policy on the relative environmental advantages of each type of system, especially comparing different technology combinations and scales of implementation. However, it is recommended that the life cycle models be adapted to a high level of specificity to match the context of application. For use at a greater scale (e.g. regional or national), the variance in local conditions and supply chains may necessitate consideration of uncertainty; for example, through Monte Carlo analysis.

It is also recommended that future LCA studies be based on electricity consumption, especially for the systems with variable generation. Furthermore, the environmental impacts and economic costs should be integrated with social aspects. Multi-objective optimisation and/or multi-criteria decision analysis can be used to determine trade-offs between different sustainability criteria and facilitate the identification of most sustainable options off-grid renewable energy systems.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgements

This work is funded by the UK Department for Business, Energy and Industrial Strategy and the Philippine Commission on Higher Education delivered by the British Council through the CHED-Newton PhD Scholarship programme (ID 261718262), as well as by the UK Engineering and Physical Sciences Research Council (EPSRC, Gr. No. EP/K011820/1). This funding is acknowledged gratefully.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.114004.

References

[1] World Bank. The welfare impact of rural electrification: a reassessment of the costs and benefits - an IEG impact evaluation (English). Washington, DC: 2008.
[2] UNDP. Sustainable Development Goals 2017. http://www.undp.org/content/undp/en/home/sustainable-development-goals.html (accessed June 19, 2017).
[3] International Energy Agency, International Renewable Energy Agency, United Nations, World Bank Group, World Health Organization. Tracking SDG7: The Energy Progress Report 2018. Washington, D.C.: 2018.
[4] International Energy Agency (IEA) and the World Bank. Global Tracking Framework 2017—Progress toward Sustainable Energy. Washington, DC, 2017. https://doi.org/10.1596/978-1-4648-1084-8.
[5] Mandelli S, Barbieri J, Meru R, Colombo E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew Sustain Energy Rev 2016;58:1621–46. https://doi.org/10.1016/j.rser.2015.12.338.
[6] IRENA. Accelerating Off-grid Renewable Energy. Manila, 2014.
[7] IRENA. Innovation Outlook: Renewable Mini-grids. Abu Dhabi; 2016.
[8] OECD/IEA. World Energy Outlook 2019. Paris: 2010.
[9] World Bank. Technical and economic assessment of off-grid, mini-grid and grid electrification technologies. Washington, DC: 2007.
[10] Chazavey A, Kandpal TC. A techno-economic comparison of rural electrification based on solar home systems and PV micro-grids. Energy Policy 2010;38:3118–29. https://doi.org/10.1016/j.enpol.2010.01.052.
[11] Mainali B, Silveira S. Alternative pathways for providing access to electricity in developing countries. Renew Energy 2013;57:299–310. https://doi.org/10.1016/j.renene.2013.01.057.
[12] D’Agostino AL, Lund PD, Urpelainen J. The business of distributed solar power: a comparative case study of centralized charging stations and solar micro-grids. Wiley Interdisciplinary Rev Energy Environ 2016;5:640–8. https://doi.org/10.1002/wrer.209.
[13] Rojas-Zepa JC, Yusta JM. Application of multicriteria decision methods for electric supply planning in rural and remote areas. Renew Sustain Energy Rev 2015;52:557–71. https://doi.org/10.1016/j.rser.2015.07.139.
[14] HOME Energy LLC. HOME Pro 2017.
[15] Liu Y, Yu S, Zhu Y, Wang D, Liu J. Modeling, planning, application and management of energy systems for isolated areas: A review. Renew Sustain Energy Rev 2018;82:460–70. https://doi.org/10.1016/j.rser.2017.09.063.
[16] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32:192–205. https://doi.org/10.1016/j.rser.2014.
01.035.
[17] Sawe Y, Gupta SC, Bohre AK. Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system. Renew Sustain Energy Rev 2018;81:2217–35. https://doi.org/10.1016/j.rser.2018.06.035.
[18] Varun, Bhat IK, Prakash R. LCA of renewable energy for electricity generation systems—A review. Renew Sustain Energy Rev 2009;13:1067–73. https://doi.org/10.1016/j.rser.2008.08.004.
[19] Barros MV, Salvador R, PiekarSKI CM, de Francisco AC, Freire FMCS. Life cycle assessment of electricity generation: a review of the characteristics of existing literature. Int J Life Cycle Assess 2019:1–19. https://doi.org/10.1007/s11367-019-01652-4.
[20] Kommalapati R, Kadival A, Shahriar M, Huque Z. Review of the life cycle greenhouse gas emissions from different photovoltaic and concentrating solar power electricity generation systems. Energies 2017;10:350. https://doi.org/10.3390/en10030350.
[21] Kabir MR, Kommalapati R, Huque Z. Characterization of the life cycle greenhouse gas emissions from wind electricity generation systems. Int J Energy Environ Eng 2017;8:55–64. https://doi.org/10.1007/s40095-016-0221-5.
[22] Kabir MR, BooKE R, Dassanayake GDM, Fleck BA. Comparative life cycle energy, emission, and economic analysis of 100 MW nameplate wind power generation. Renew Energy 2012;37:133–41. https://doi.org/10.1016/j.renene.2011.06.003.
[23] Turconi R, Baldin A, Astrap T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sustain Energy Rev 2013;28:555–65. https://doi.org/10.1016/j.rser.2013.08.013.
[24] Smith C, Burrows J, Scheier E, Young A, Smith J, Young T, et al. Comparative Life Cycle Assessment of a Thai Island’s diesel/PV/wind hybrid micro-grid. Renew Sustain Energy Rev 2015;42:1113–22. https://doi.org/10.1016/j.rser.2014.10.072.
[25] Benton K, Yang X, Wang Z. Life cycle energy assessment of a standby diesel generator set. J Clean Prod 2017;149:265–74. https://doi.org/10.1016/j.jclepro.2017.02.082.
[26] Jungbühler N, Stucki M, Flury K, Frischknecht R, Büsser S. Life cycle inventories of photovoltaics. 2012.
[27] Greening B, Azapagic A. Environmental impacts of micro-wind turbines and their potential to contribute to UK climate change targets. Energy 2013;59:454–66. https://doi.org/10.1016/j.energy.2013.06.037.
[28] Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zähr R, et al. Contribution of li-ion batteries to the environmental impact of electric vehicles. Environ Sci Technol 2010;44:6550–6. https://doi.org/10.1021/es903729u.
[29] Burger B, Bauer C, Windkraft, In: Dones R, Meier S, editors. Schaltblanzen von Energieversystemen. Final Rep. No. 6 ecoinvent data v2.0, Dubendorf and Villigen: Swiss Centre for LCI, PSI, 2007.
[30] JICA/Ex Corporation. The Study on Recycling Industry Development in the Republic of the Philippines. Tokyo: 2008.
[31] Glöser S, Soulier M, Tercero Espinoza LA. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. Environ Sci Technol 2013;47:6564–72. https://doi.org/10.1021/es400669r.
[32] BIR Ferrous Division. World Steel Recycling in Figures 2011–2015. Brussels: 2016.
[33] Tse P-K. The Mineral Industry of China. US Geol. Surv. Miner. Yearb. 2013, US Geological Survey, 2015.
[34] ThInkstep. GaBi Software-System and Database for Life Cycle Engineering; 2016.
[35] Goodkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008 version 1.08. The Hague; 2013.
[36] De Schryver AM, van Zelm R, Humbert S, Pfister S, McKone TE, Huijbregts MAJ. Value choices in life cycle impact assessment of stressors causing human health damage. J Ind Ecol 2011;15:796–815. https://doi.org/10.1111/j.1530-9290.2011.00371.x.
[37] Fibenakis V, Kim HC, Frischknecht R, Rausch M, Sinha P, Sticki M. Life cycle inventories and life cycle assessments of photovoltaic systems. New York: 2011.
[38] Claassen M, Althaus J-H, Blaser S, Tuchschild M, Jungbluth N, Doka G, et al. Life Cycle Inventories of Metals. Final Rep. ecoinvent data v2.1, Dubendorf; 2009.
[39] Guo M. LCA Case Studies of Starch-Based Foam. Final Rep. ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Inventories and framework. Geneva: International Organization for Standardization; 2006.