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Synergistic generation of energy and water in remote communities: Economic and environmental assessment of current situation and future scenarios

Jhud Mikhail Aberilla^{a,b}, Alejandro Gallego-Schmid^{a,c}, Laurence Stamford^a and Adisa Azapagic^{a,*}

^a Sustainable Industrial Systems, Department of Chemical Engineering and Analytical Science, The University of Manchester, The Mill, Sackville Street, Manchester M13 9PL, UK

^b Department of Chemical Engineering, University of the Philippines, C.P. Garcia Avenue, Diliman, Quezon City 1101, Philippines

^c Tyndall Centre for Climate Change Research, Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Pariser Building, Sackville Street, Manchester M13 9PL, UK

* Corresponding author. E-mail address: adisa.azapagic@manchester.ac.uk (A. Azapagic).

Abstract

Improving access to energy and water in remote communities is an important step towards sustainable development. However, integrated sustainability studies at the community or household scale are rare compared to industrial or national studies. Thus, this paper presents an integrated approach to the development and evaluation of energy and water supply systems in remote communities in developing countries. Termed here “synergistic generation” (“synergen”), the approach considers simultaneously electricity, heat for cooking and water supply to determine their environmental and economic sustainability on a life cycle basis. Life cycle assessment and life cycle costing are used for this purpose. Both the current situation and future scenarios to 2030 are considered for a representative remote community. The life cycle costs of the current energy and water supply are estimated at 2,944 USD/ household per year, most of which (91%) is due to bottled water. The latter is also the main cause of current environmental impacts (62%), followed by cooking fuels (33%) and electricity (5%). If business as usual (BAU) continues to 2030, air pollution and eutrophication could be reduced by >40% but other 14 impacts would increase by 2–63% on the current situation due to higher dependence on diesel for electricity generation and bottled water. For the same reason, BAU also has 82% higher life cycle costs (5,364 USD/household·yr) than at present. Assuming full supply self-sufficiency (Independent scenario) leads to a >12% reduction in all impact categories, except terrestrial ecotoxicity, which increases by 5% - both trends are due to utilisation of waste biomass for cooking. The life cycle costs are reduced by 92% (231 USD/household·yr), mainly due to the phasing out of bottled water. However, capital costs are 21% higher due to the need for multiple renewable energy installations. Pursuing moderate rather than full independence of supply (Transition scenario) would reduce most impacts and costs below those of the current situation. Overall, the Transition and Independent scenarios have lower impacts than at present in almost all environmental categories as well as lower life cycle costs. These findings demonstrate the environmental and economic feasibility of energy and water independence in remote communities as well as highlighting the likely trade-offs that should be considered during the transition.

Keywords: *Household cooking heat; Life cycle assessment; Life cycle costing; Off-grid electricity; Rural development.*

Nomenclature

ACC _j	Annualised capital costs of technology/option j (USD/yr)	LCC	Total life cycle cost (USD/hh·yr)
C	Set of cooking fuels	LCOE	Levelised cost of electricity (USD/hh·yr)
CC _j	Capital costs of technology/option j (USD)	LCOH	Levelised cost of cooking heat (USD/hh·yr)
CFC _{hh}	Annual cooking heat consumption per household (MJ/hh·yr)	LCOW	Levelised cost of locally-produced water (USD/hh·yr)
CFS	Total cooking heat consumption of by the community (MJ/yr)	n	Lifetime of technology/option j (yr)
E	Set of electricity generation components	OMC _j	Operating and maintenance costs of technology/option j (USD/yr)
EC _{hh}	Annual electricity consumption per household (kWh/hh·yr)	PCBW	Annual purchase costs of imported bottled water (USD/hh·yr)
El _{j,k}	Unit environmental impact k from technology/option j for each utility (per kWh, MJ or m ³)	VC _j	Annual variable costs of technology/option j (USD/yr)
El _{k,hh}	Total annual environmental impact k per household (kWh, m ³ or kg eq.)	W	Set of water supply options
ES	Total electricity consumption by the community (kWh/yr)	WC _{hh}	Annual water consumption per household (m ³ /hh·yr)
FC _j	Annual fixed costs of technology/option j (USD/yr)	WS	Total water consumption by the community (m ³ /yr)
fC _j	Fuel costs of technology/option j (USD/yr)	X _j	Share of technology/option j in the supply mix (-)
i	Discount rate		

1. Introduction

Access to electricity, clean cooking and safe water is identified as key for achieving many of the United Nations' Sustainable Development Goals (SDG) [1]. While progress has been made in recent years, the rate of population growth overtakes the improvement of access in many developing countries for both energy [2] and water [3]. Planning of energy and water services in these regions is further complicated by the complex interactions of these resources within the energy-water nexus [4]. For example, distributed electricity generation, such as production of biogas from manure, can affect quality of water supply due to the leachates from the digestate [5].

Methodologies in systems engineering have been highlighted as effective tools for incorporating the nexus into conventional engineering design and policy formulation [6]. Previous studies have used integrated modelling frameworks including systems dynamics [7], agent-based modelling and network optimisation [4], superstructures [8], process simulation [9] and life cycle assessment (LCA) [10] to address the nexus in energy and water production systems. For example, Leung Pah Hang et al. [8] developed an integrated model for food, energy and water production for a master-planned greenfield eco-town. The study highlighted that co-designing the sub-systems, compared to designing each supply chain separately, reveals the synergies and new options available to designers. However, the authors noted that their problem formulation is not applicable for pre-existing installations. In a similar study, Al-ansari et al. [10] showed how extending the scope of LCA to the energy-water-food nexus can relate consumption and production at a national level to an overall environmental impact. However, compared to the national or regional levels, studies of the nexus at the household and community scales are limited. One such study [7] used a scenario analysis to consider the interactions between water-energy-food parameters and the drivers of household consumption. Furthermore, the previous studies have considered only one dimension of sustainability (e.g. economic or environmental) so that their trade-offs remain unexplored.

A related concept in simultaneous energy and water production is polygeneration, a term used to describe integrated processes which provide multiple products, such as fuels, chemicals [11] and utilities [12]. Although many studies in polygeneration design focus on industrial-scale production, there is a growing interest in smaller scale polygeneration systems [13]. Previous studies on polygeneration for remote communities presented designs sized to meet the demand at a certain location. For example, Khan et al. [14] performed a techno-economic analysis of a biogas system to meet the electricity, cooking and water demands of a 30-household village in Bangladesh. While their design provided acceptable levelised costs of utilities, capital costs and biomass availability were the key barriers for implementation. A polygeneration system proposed by Calise et al. [15]

consisted of four technologies for supplying electricity, space heating and cooling, as well as water to a sub-urban area of an Italian island. Their work focused on developing the simulation models although they also provided estimates for avoided diesel consumption and its related CO₂ emissions. Another study [16] considered a solar-assisted micro-gas turbine system to generate electricity, heat (for domestic hot water) and space cooling for a remote village of 25-50 households in Israel. In comparison to the existing diesel generator, air conditioning units and diesel-fired water heaters, this system had lower costs and CO₂ emissions. However, all these analyses suppose that existing utility systems are not present or are completely replaced by the proposed design. Furthermore, dependence on a single polygeneration facility to provide for the utility requirements of a community affects the security of supply, especially in disaster-prone areas. Besides, in some instances, replacing current systems with polygeneration does not lead to environmental benefits. This is the case, for example, when the carbon intensity of the current system is sufficiently low compared to achievable efficiencies of combined systems [17]. Therefore, there is a need for comprehensive life cycle assessments to determine whether integrated energy and water systems are beneficial environmentally.

To address some of the above deficiencies of single-plant polygeneration of off-grid utilities, this paper proposes an alternative approach by considering multiple production systems working in synergy with each other within the energy-water nexus. Rather than constraining the design space to a single installation to provide all of the demands, the proposed approach – termed here “synergen” – investigates and takes advantage of multiple and intersecting supply chains. The study combines scenario analysis, techno-economic simulation and optimisation, life cycle costing (LCC) and LCA to design economically and environmentally sustainable systems for supplying electricity, cooking heat and water in remote communities to benefit from synergies that exist between them. This work contributes to the literature by providing an alternative approach in the planning, design and evaluation off-grid utility systems. Furthermore, it demonstrates the potential of remote communities to have independent utility systems that have improved economic and environmental performance compared to the current situation. As far as the authors are aware, this is the first study of its kind internationally.

2. Methods

As outlined in Figure 1, the methodology applied in this study comprises the following steps: i) definition of the goal and scope of the study; ii) definition of the current energy and water supply systems and simulation of the electricity supply; iii) definition of future scenarios and design and optimisation of feasible electricity synergen systems; and iv) evaluation of the economic and environmental sustainability of the current situation and future scenarios to identify the most sustainable option(s).

HOMER Pro [18] has been utilised to simulate the current electricity system as well as to design and optimise future electricity systems according to different scenarios. The economic sustainability has been evaluated via LCC in accordance with the methodology proposed by Swarr et al. [19]. LCA has been used to assess the environmental sustainability, following the guidelines in ISO 14040/14044 [20,21] and taking an attributional approach. The above methodological steps are described in turn in the next sections.

2.1 Goal and scope definition

As previously mentioned, the goal of the study is to design environmentally and economically sustainable energy and water systems for remote communities, to maximise the benefits of their synergistic interactions. Both the current situation and possible future scenarios are considered. The base year for the current situation is 2015, based on data availability. For the scenarios, the year 2030 has been selected to correspond to the time horizon of the SDG.

Figure 1. Methodology for designing and evaluating the sustainability of synergen systems

The Philippines has been selected as the geographical context for the study. This is due to its numerous off-grid small-island communities [22] and the country's ambition to transition towards sustainable energy [23]. The average community in off-grid islands has 4,534 households (with on average four persons) [24], forecasted to grow to 5,588 households by 2030 [25]. As an archipelagic nation, the Philippines has a rural electrification rate of 85%, leaving an estimated 11 million people without electricity as of 2016 [26]. Only 45% of the population has access to clean fuels and technologies, making the Philippines one of the bottom 20 countries in the world [2]. Water access, as measured by having 'basic water service', is at 90.5% in the country, but a gap of more than 10 points exists between urban (96.4%) and rural (85.8%) areas [27]. Similar conditions exist in island and other remote communities in the rest of Southeast Asia as well as in the Caribbean and Oceania [28].

The analysis is based on the functional unit defined as "annual consumption of electricity, cooking fuels and water per household". Assuming basic access to the utilities in the remote communities in the region, this is equivalent to 100 kWh of electricity [29], 4.87 GJ of heat for cooking [30] and 197 m³ of water [31]. Space heating is not considered due to the tropical climate; cooling is excluded at this basic level of energy access.

The scope of the study is from cradle to grave, comprising raw materials extraction, installation, maintenance, use and eventual end of life of facilities. Figure 2 shows the system boundary for the life cycles of electricity, cooking and water supply as well as their synergistic interactions. For example, biomass is used for electricity generation and as a cooking fuel, while electricity is consumed for cooking (electric stoves) and water extraction. The infrastructure and the fuels considered in the study are also given in Figure 2.

2.2 Current situation

As is the case for most remote communities, off-grid power systems in the Philippines are dominated by diesel generators (>96% of capacity and generation) [22]. The operation of the diesel generator has been simulated in HOMER, considering the residential load profile (Figure 3) and the power required for water production (Table 1). Techno-economic parameters, such as fuel consumption and operating costs, have been obtained through the simulation. For further details, see Aberilla et al. [32].

Figure 2. System boundary for the electricity, cooking heat and water synergen system (Upstream processes, transport and end-of-life waste management are not shown but are included in the system. Imported water: bottled water supplied externally.)

The most recent household survey in the Philippines shows that liquefied petroleum gas (LPG) is the preferred heat source for domestic cooking, supplying 39.8% of the cooking energy demand (Figure 4a) [30]. However, traditional biomass fuels (fuel wood, charcoal and other biomass) are still prevalent in rural areas, with a total share of 55.8% [33]. For this study, other biomass fuels are taken to be crop residues from rice and coconut farming as these are the most common crops planted in the region [34]. The rest of the cooking fuel demand is met by kerosene (4.4%).

The water sources used by households in the Philippines [24] are summarised in Figure 4b, excluding those with access to tap water. The fraction of households primarily using water mains corresponds roughly to the fraction of the population residing in urban areas of the country. Hence, it can be inferred that remote communities obtain most of their water from local ground and surface water sources or purchase bottled water. The latter is sourced externally, referred to here as 'imported' water, packaged either in reusable 18.9 L containers (5 gallon) or single-use 1.5 L bottles.

Figure 3. Current hourly residential load profile per household [18] (Total annual electricity consumption: 100 kWh)

Table 1. Parameters used in HOMER for simulation of the current electricity supply

Item	Parameter	Value
Residential load (alternating current)	Average (kWh/d)	621
	Average (kW)	25.88
	Peak (kW)	115.3
	Load factor	0.22
Water load (alternating current) ^a	Annual average (kWh/d)	563
	Storage capacity (kWh)	99.62
	Peak load (kW)	47
Diesel generator ^a	Minimum load ratio	25%
	Lifetime (h)	15,000

^a Models used in HOMER: Water load: deferrable; Diesel generator: generic medium.

Figure 4. (a) Cooking fuel mix [30] and (b) potable water supply [24] in off-grid Philippine households

[Other biomass fuels are assumed to be crop residues from rice and coconut farming.]

2.3 Future scenarios

The following three scenarios are considered: Business as usual (BAU), Transition and Independent. They follow different paths in terms of technologies, access and security of supply as described below.

The BAU scenario considers no change in the source of electricity on the current situation. Hence, the off-grid electricity continues to be reliant solely on diesel generators, with capacity expansion expected to meet the demand increase due to the population growth and greater access to energy (Table 2). As indicated in Figure 5, the cooking fuel mix sees an increase in LPG and introduction of biogas to offset the trend of a decreasing use of traditional biomass and kerosene as households move towards cleaner fuel options [35,36]. Only a small fraction of electricity (<1%) is used for cooking purposes [29]. Extraction from natural freshwater sources is expected to increase [37], but this will not be enough to match the increase in population; therefore, households are expected to purchase more bottled water as a result (Figure 6).

In the Transition scenario, existing energy and water options are still preferred, but renewable technologies are also introduced in the supply mix. These include solar photovoltaics (PV), wind turbines, bio-syngas from gasification of crop residues and biogas from anaerobic digestion of animal manure. These renewables have been selected as they are recommended for small-scale electrification in developing countries [38]. For the cooking fuel sector, total LPG consumption is kept at current levels, with biogas and traditional biomass filling in the remaining demand in the same proportions as in the BAU scenario (Figure 5). The water supply follows the same trend as in BAU, except that the total imported water is kept constant at current levels and seawater desalination is used to meet the supply gap (Figure 6). The energy-water nexus can be noticed in

this scenario: animal manure is a common resource for both electricity and cooking fuels, while additional power is required for electric stoves and water desalination.

Table 2. Electricity demand in the current situation and future scenarios

Parameter	Current situation	Business as usual	Transition	Independent
No. of households	4,534	5,588	5,588	5,588
Households with electricity (%)	50	100	100	100
Residential demand (kWh/hh·yr)	100	112 ^a	112 ^a	112 ^a
Electricity for water production (kWh/hh·yr)	45	40	148	231
Total demand (kWh/hh·yr) ^b	95	152	260	343

^a Including 12 kWh/hh·yr of electricity for cooking.

^b Total demand = (Number of households x Percentage of households with access x Residential demand) + Electricity for water production.

Table 3. Parameters used in HOMER for simulation and optimisation of electricity supply in the future scenarios

Item	Parameter	Value
Resources	Location	10°16'N, 119°30'E
	Average solar resource (kWh/m ² /d)	5.27
	Average wind resource (m/s)	5.66
Residential load (alternating current)	Average (kWh/d)	Varies with scenario (Table 2)
	Average (kW)	4% of daily load
	Peak (kW)	11% of daily load
	Load factor	0.22
Water load, current (alternating current, deferrable)	Annual average (kWh/d)	Varies with scenario (Table 2)
	Storage capacity (h/d)	4
Diesel generator ^a	Minimum load ratio	25%
	Lifetime (h)	15,000
Solar PV ^a	Derating factor	80%
	Lifetime (yr)	30
Wind turbine ^a	Hub height (m)	29
	Lifetime (yr)	20
Li-ion battery ^a	Initial state of charge	100%
	Minimum state of charge	20%
	Degradation limit	30%
System converter ^a	Inverter efficiency	95%
	Rectifier efficiency	90%
	Lifetime (yr)	15
Biogas ^a	Minimum load ratio	20%
	Reference capacity (kW)	300
	Lifetime (h)	50,000

^a Models used for modelling in HOMER: Diesel generator: generic medium; Wind turbine: NPS100C-24; PV: generic flat plate; Battery: generic advanced storage module; Converter: generic; Biogas: generic size-your-own.

Figure 5. Cooking fuel mix for the current situation and future scenarios

Figure 6. Water supply mix for the current situation and future scenarios

The Independent scenario assumes community self-sufficiency, with utility sectors operating independently of external fuel and water resources. In this scenario, diesel generators and LPG are phased out, with the entire electricity supply relying on the renewables. Battery storage is introduced to mitigate the intermittency of supply by solar PV and wind. Li-ion batteries are selected as they need less frequent replacement [39] and have lower environmental impacts than lead acid batteries [32]. Kerosene and imported water are no longer used either, with the resulting cooking fuel and water supply mix given in Figure 5 and Figure 6, respectively.

The hourly electricity supply in the scenarios has been simulated and cost-optimised in HOMER based on the data in Table 2 and Table 3, taking into account the increase in demand for cooking and water desalination in relevant scenarios. Availability of biomass in the representative community considered in the study, which can be used for either electricity production or cooking fuel, is estimated at 12,000 t/yr of crop residues and 68,000 t/yr of animal manure [40,41]. These are included in the analysis as constraints. The optimised electricity mix in each scenario is discussed in section 3.1.

2.4 Life cycle costing

The total life cycle costs of the utilities for the current situation and the future scenarios have been estimated per household as the sum of costs of the electricity, cooking fuels and water:

$$LCC = LCOE + LCOH + LCOW + PC_{BW} \quad (1)$$

where:

LCC	total life cycle cost (USD/hh·yr)
LCOE	levelised cost of electricity (USD/hh·yr)
LCOH	levelised cost of heat for cooking (USD/hh·yr)
LCOW	levelised cost of locally-produced water (USD/hh·yr)
PC _{BW}	annual purchase costs of imported bottled water (USD/hh·yr).

The levelised costs of different utilities are equal to the sum of annualised capital, operating and maintenance cost of each technology providing each utility type:

$$LCOE = \sum_{j \in E} x_j (ACC_j + OMC_j) \times \frac{EC_{hh}}{ES} \quad (2)$$

$$LCOH = \sum_{j \in C} x_j (ACC_j + OMC_j) \times \frac{CFC_{hh}}{CFS} \quad (3)$$

$$LCOW = \sum_{j \in W} x_j (ACC_j + OMC_j) \times \frac{WC_{hh}}{WS} \quad (4)$$

where:

ACC _j	annualised capital costs of technology/option <i>j</i> (USD/yr)
OMC _j	operating and maintenance costs of technology <i>j</i> (USD/yr)
x _j	share of technology/option <i>j</i> in the supply mix (-)
E	set of electricity generation components
EC _{hh}	annual electricity consumption per household (kWh/hh·yr)
ES	total electricity consumption by the community (kWh/yr)
C	set of cooking fuels
CFC _{hh}	annual cooking heat consumption per household (MJ/hh·yr)
CFS	total cooking heat consumption of by the community (MJ/yr)
W	set of water supply options
WC _{hh}	annual water consumption per household (m ³ /hh·yr)
WS	total water consumption by the community (m ³ /yr).

Capital costs comprise purchase, transport and installation of infrastructure and are annualised using a discount rate of 10%, commonly used for energy systems in non-OECD countries [42]:

$$ACC_j = CC_j \times \frac{i(1+i)^n}{(1+i)^n - 1} \quad (5)$$

where:

CC _j	capital costs of technology <i>j</i> (USD)
<i>i</i>	discount rate
<i>n</i>	lifetime of technology <i>j</i> (yr).

The operating and maintenance costs include both fixed and variable maintenance expenses as well as fuel costs:

$$OMC_j = FC_j + VC_j + fC_j \quad (6)$$

where:

FC _j	annual fixed costs of technology/option <i>j</i> (USD/yr)
VC _j	annual variable costs of technology/option <i>j</i> (USD/yr)
fC _j	fuel costs of technology/option <i>j</i> (USD/yr).

For the water supply, purchase costs of imported bottled water (PC_{BW} in eq. (1)) are accounted for separately from the capital and operating costs since the community is not responsible for the production facilities of bottled water.

Data used for the economic analysis are summarised in Table 4. They have been sourced from own estimates and modelling in HOMER as well as from the literature. The latter have been selected to correspond to small-scale installations and rural developing countries. Future costs of power technologies and fuels have been estimated based on learning curves and market outlooks [43–46]. For consistency, all costs are expressed in 2015 US dollars (USD).

Table 4. Cost data

Item	Cost ^a	Value	Reference
Diesel generator	Capital costs (USD/kW)	650	Lazard [47]
	Operating costs: fixed (USD/kW·yr)	10	Lazard [47]
	Operating costs: variable (USD/kWh)	0.01	Lazard [47]
	Fuel costs (2015, USD/L)	0.92	IndexMundi [48]
	Fuel costs (2030, USD/L)	2.12	OECD/IEA [43]
Solar PV	Capital costs (2030, USD/kW)	1,088	Lazard [47], IRENA [44]
	Operating costs (2030, USD/kW·yr)	14	Lazard [47]
Wind turbine	Capital costs (2030, USD/kW)	3,496	Orrell [49], IRENA [44]
	Operating costs (2030, USD/kWh·yr)	0.03	IRENA [50]
Anaerobic digestion (for electricity)	Capital costs (2030, USD/kW)	1,660	IRENA [51]
	Operating costs: fixed (2030, USD/kW·yr)	166	IRENA [42]
	Operating costs: variable (2030, USD/MWh)	4.5	IRENA [42]
	Feed costs (USD/t)	0.05	Own calculations
Li-ion battery	Capital costs (2030, USD/kWh)	341	Lazard [52], IRENA [45]
	Operating costs (2030, USD/kWh·yr)	25	IRENA [39]
System converter	Capital costs (2030, USD/kW)	180	IRENA [44]
Cooking stove	Capital cost: biogas (USD)	48	Afrane et al. [53]
	Capital cost: electric (USD)	34	Afrane et al. [53]
	Capital cost: LPG (USD)	25	Afrane et al. [53]
	Capital cost: kerosene and solid biomass (USD)	20	Wilson et al. [54], Jana et al. [55]
Anaerobic digestion (for cooking fuel)	Capital costs (2030, USD, 8 m ³ capacity)	540	Baron [56]
	Operating costs (2030, USD/yr)	14.31	IRENA [42]
	Feed costs (USD/t)	10.91	Own calculations
	Digestate selling price (USD/t)	11.26	Own calculations
Cooking fuel	Charcoal (USD/kg)	0.16	Afrane et al. [53]
	Fuel wood (USD/kg)	0.05	Afrane et al. [53]
	Crop residues (USD/t)	10.44	Own calculations
	LPG (2015, USD/L)	0.10	IndexMundi [48]
	LPG (2030, USD/L)	0.28	OECD/IEA [43][43,48]
	Kerosene (2015, USD/L)	0.26	IndexMundi [48]
	Kerosene (2030, USD/L)	0.72	OECD/IEA [43]
	Capital costs (USD)	10,705	Marchionni et al. [57], Towler and Sinnott [58]
Water pump	Capital costs (USD)	14,979	Towler and Sinnott [58]
	Operating costs (USD/m ³)	0.05	Towler and Sinnott [58]
Desalination plant	Capital costs: reverse osmosis module (USD)	4,756	Banat and Jwaied [59], Kosmadakis et al. [60], Garg and Joshi [61]
	Capital costs: balance of system (USD)	26,949	Papapetrou et al. [62]
	Operating costs (USD/m ³) ^b	0.20	Shahabi et al. [63], Ettouney et al. [64]
Imported water	Price: 1.5-L bottled water (USD/m ³)	342	DTI [65]
	Price: 18.9-L water (USD/m ³)	46	Philippine Primer [66]

^a If no year is specified, the costs are the same for the current situation and the future scenario.

^b Not including cost of electricity, which is estimated through HOMER simulations for each scenario (see section 3.1).

Table 5. An overview of inventory data and sources for different components of the synergen system

Technology	Infrastructure	Operation and maintenance	Fuel
Solar photovoltaics	Multi-Si wafer, 155.9 Wp/m ² [67], ground-mounted installation [68]	20 L/m ² water for cleaning [69]	-
Wind turbine	100-kW onshore installation [70]	0.04 kg/kWh lubricating oil [69]	-
Diesel generator	Material composition from Benton et al. [71], scaled ^a	Emissions from Ecoinvent [69]	Diesel refining [69] and transportation [32]
Li-ion battery	LiMn ₂ O ₄ cathode and graphite anode [72]	-	-
System converter	2.5-kW units [68]	-	-
Biomass gasification	Gasifier scaled down to 18 kW from Adams [73], coupled with gas turbine [69]	Yield from Aberilla et al. [74], emissions from Ecoinvent [69]	Rice and coconut residues [74]
Anaerobic digestion	8 m ³ home biogas system [56], coupled with gas turbine [69] for electricity generation	Yield from Aberilla et al. [74], emissions from Ecoinvent [69]	Manure from livestock [74]
LPG/kerosene cooking	Gas stove [75]	Emissions from Singh et al. [76], 46-57% stove efficiency [77]	Petroleum refining [69] and transportation [78]
Solid biomass cooking	Berkeley-Darfur stove [54]	Emissions from Singh et al. [76], 11-25% stove efficiency [77]	Fuel wood, charcoal [76], rice and coconut residues [74]
Biogas cooking	Gas stove [75]	Emissions from Singh et al. [76], 55-57% stove efficiency [77]	Biogas from anaerobic digestion
Electric cooking	Electric stove [75]	59-80% stove efficiency [77]	-
Ground water extraction	Tube well and pump [79]	0.35 kWh/m ³ [79], chlorine tablets for disinfection [69]	-
Surface water extraction	Water tank [79]	Chlorine tablets for disinfection [69]	-
Desalination	Based on 13.5 m ³ /d capacity [80]	4.17 kWh/m ³ [81], chemicals for maintenance [63]	-
Bottled water (1.5-L bottle)	Pumping station operating on-grid [69]	Operation of pumping station [69] and bottling [82]	-
Bottled water (18.9-L bottle)	Pumping station operating on-grid [69]	Operation of pumping station [69], bottling and cleaning of reusable containers [82]	-

^a The mass of materials used to construct the generator estimated as: $m = 101.7 \cdot (\text{Installed capacity})^{0.56}$ (own calculations).

2.5 Life cycle assessment

This section gives an overview of the life cycle inventory data and the impact assessment method used in the study.

2.5.1 Life cycle inventory

An overview of the inventory data and their sources is provided in Table 5 for each technology and utility. These data have been used to model the utility systems in the current situation and future scenarios in GaBi ts 7.3 [83], supported by background data from ecoinvent 3.1 [69]. The system has been credited for displacing mineral fertilisers by ash from biomass and digestate from anaerobic digestion [74]. Further details on the individual technologies can be found in Aberilla et al. [32,74,78] and Aberilla [81]; the focus here is on their synergistic integration to consider the impacts at present and in the future scenarios.

2.5.2 Life cycle impact assessment

Life cycle environmental impacts have been estimated applying the ReCiPe 1.08 (H) method [84] with 18 midpoint impacts, grouped by the environmental issue they cause, as shown in Table 6.

Table 6. Indicators for environmental sustainability assessment

Environmental issue	Impact	Unit
Climate change	Global warming potential (GWP), excluding biogenic carbon	kg CO ₂ eq.
Air pollution	Ozone depletion potential (ODP)	kg CFC-11 eq.
	Photochemical oxidant formation potential (POFP)	kg NMVOC ^a eq.
	Particulate matter formation potential (PMFP)	kg PM ₁₀ eq.
Eutrophication and acidification	Freshwater eutrophication potential (FEP)	kg P eq.
	Marine eutrophication potential (MEP)	kg N eq.
	Terrestrial acidification potential (TAP)	kg SO ₂ eq.
Biodiversity	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB ^b eq.
	Marine ecotoxicity potential (METP)	kg 1,4-DCB ^b eq.
	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB ^b eq.
Resource depletion	Fossil depletion potential (FDP)	kg oil eq.
	Mineral depletion potential (MDP)	kg Fe eq.
	Water depletion potential (WDP)	m ³
Land use	Agricultural land occupation potential (ALOP)	m ² ·yr
	Natural land transformation potential (NLTP)	m ²
	Urban land occupation potential (ULOP)	m ² ·yr
Human health	Human toxicity potential (HTP)	kg 1,4-DCB ^b eq.
	Ionising radiation potential (IRP)	kg U ²³⁵ eq.

^a Non-methane volatile organic compounds.

^b 1,4-dichlorobenzene.

To determine the total impact per functional unit (i.e. per household-year), the impact from each technology has been weighted and summed according to its contribution to the supply mix of each utility as follows:

$$EI_{k, hh} = EC_{hh} \sum_{j \in E} x_j EI_{j, k} + CFC_{hh} \sum_{j \in C} x_j EI_{j, k} + WC_{hh} \sum_{j \in W} x_j EI_{j, k} \quad (7)$$

where:

$EI_{k, hh}$ total annual environmental impact k per household (kWh, m³ or kg eq.)

$EI_{j, k}$ unit environmental impact k from technology j for each utility (per kWh, MJ or m³).

As with the life cycle costing, the share of the cooking heat and water supply provided by each source has been obtained through the scenario definitions (section 2.3), while those for the electricity supply have been determined through simulation in HOMER.

3. Results and discussion

The results of the simulation to meet the overall power demand in the current situation and future scenarios are presented in the next section. These are integrated with the scenario definitions for cooking and water in section 2.3 to obtain the overall utility supply in the different scenarios. Then, the economic and environmental impacts of the utility systems in the current situation are assessed in section 3.2. This is followed in section 3.3 by an equivalent discussion of the results for the future scenarios.

3.1 Electricity supply in the current situation and future scenarios

Following the synergen approach, the simulation of the current and design and cost-optimisation of future electricity systems considers both the residential demand and the electricity needed for local water supply. To meet the current demand of 95 kWh/hh·yr (Figure 7), a 100-kW diesel generator operating continuously (8760 h/yr) has been sized in HOMER. As a result, 133,843 L/yr (30 L/hh·yr) of diesel is required (Table 7) in load-following operation at a mean efficiency of 33%.

For the consumption of 152 kWh/hh·yr electricity in the BAU scenario (Figure 7), additional diesel-generator capacity is required, bringing the total to 300 kW. Still operating 8760 h/yr, the generator consumes 300,724 L/yr (54 L/hh·yr) of fuel (Table 7) at a slightly lower mean efficiency of 30%, as determined by the hourly load simulation in HOMER.

Unlike the BAU, the power demand in the Transition and Independent scenarios is derived more from water production (especially desalination) than direct residential consumption). The 100-kW diesel generator is retained in the Transition scenario, but it only contributes 1% to the total power supply of 0.6 kWh/hh·yr (Figure 7) as it is primarily used for peak operation. Most of the electricity (75%) is provided by the gas turbine fed by bio-syngas from the biomass gasifier (Table 7). Energy storage is not required as the gas turbine and diesel generator can balance the intermittent supply by solar PV and wind.

Figure 7. Electricity generation and consumption in the current situation and future scenarios (Direct residential load: electricity consumed directly by the household, including for cooking. Total load: direct residential load plus the power consumed for water production. The values shown above the bars correspond to the total load.)

In the Independent scenario, diesel is phased out and the electricity demand of 343 kWh/hh·yr is supplied by solar PV, wind and biomass gasification (Figure 7). The latter is the main source of power (71%) and solar output is more than eight times greater than in the Transition scenario. Li-ion battery is selected by the optimisation model as a backup for solar PV and wind turbine (Table 7).

The outputs of the simulation and optimisation of the electricity synergen system related to the infrastructure and fuel requirements have been used as an input into the LCA models to estimate the environmental impacts of electricity generation and consumption. The cost estimations have been used to determine the life cycle costs of the systems, as discussed next.

Table 7 The electricity system in the current situation and future scenarios^a

System component	Current	Business as usual	Transition	Independent
Diesel generator (kW)	100	300	100	-
Diesel fuel (L/yr)	133,843	300,724	2,570	-
Operating hours (h/yr)	8,760	8,760	159	-
Solar PV (kWp)	-	-	35.7	214
Wind turbine (kW)	-	-	100	100
Gas turbine, anaerobic digestion (kW)	-	-	50	-
Biomass fuel (t/yr)	-	-	5,370	-
Operating hours (h/yr)	-	-	2,330	-
Gas turbine, biomass gasification (kW)	-	-	200	300
Biomass fuel (t/yr)	-	-	2,335	2,914
Operating hours (h/yr)	-	-	6,421	4,856
Li-ion battery (kWh)	-	-	-	194
Expected life (yr)	-	-	-	15
System converter (kW)	-	-	10	179

^a The results correspond to the whole community (4,534 households in the current situation and 5,588 in 2030), obtained through simulation (current situation) and design and optimisation (future scenarios) in HOMER.

3.2 Current situation

The economic and environmental sustainability of the current situation is evaluated below and used as a reference for comparison with the sustainability of future scenarios in section 3.3.

3.2.1 Economic sustainability assessment

The current annual LCC are estimated at 2,944 USD per household (Figure 8). This is largely due to the costs of imported water, which contributes 91% to the total (2,677 USD/hh·yr). Locally-sourced water and cooking heat add a further 7% to the total and electricity the remaining 2% (220 and 46 USD/hh·yr, respectively).

Total annualised capital costs are equivalent to 107 USD/hh·yr (Figure 9), with 79% derived from infrastructure for local water production. The diesel generator comprises 16% of the capital investment, while cooking stoves account for 6%. Operating and maintenance costs are higher at 160 USD/hh·yr (Figure 10), with the majority (65%) spent on cooking fuels. Of the 30 USD/hh·yr operating and maintenance costs of the diesel generator, 96% is due to fuel. Electricity accounts for 78% of the operating costs of the water supply, again highlighting the interactions between the energy and water sectors.

Per unit of utility, the levelised costs of the current supply mix are 0.46 USD/kWh of electricity, 22 USD/GJ of heat for cooking, 0.63 USD/m³ of locally produced water and 104 USD/m³ of imported water (Table 8). Based on the annual consumption (functional unit) this amounts to the above-mentioned total LCC of 2,944 USD/hh·yr with imported water and 267 USD/hh·yr without it. The latter compares well with reported census data for utility expenses of four-person households in southwest Philippines (135-330 USD) [24].

For electricity and heat for cooking, the costs are driven by fuel costs, which account for 62% and 95% of the total, respectively. As indicated in Table 8, charcoal and fuel wood have the highest

costs per heat provided (42.78 and 33.65 USD/GJ, respectively) due to the low stove efficiencies. The cheapest fuel is crop residues at 7.17 USD/GJ.

For water, the largest unit cost is for imported bottled water: 46 USD/m³ for 18.9-L containers and 342 USD/m³ for 1.5-L bottles (Table 8). This is 3-4 orders of magnitude more expensive than surface or ground water: 0.34 and 0.80 USD/m³, respectively (including the cost of electricity). Purchase costs increase the life cycle cost of water supply to 14.15 USD/m³. Despite the high cost of bottled water, its consumption can be significant in households, regardless of income or availability of tap water [85,86]. Negative public perceptions of the safety of tap water and trustworthiness of water supplies are commonly-identified drivers for bottled water consumption [86]. In addition, bottled water can also be brought into remote communities as part of disaster relief efforts (e.g. in response to typhoons [87]); hence, the costs may not be fully borne by the residents. For context, 1,586 recorded natural disasters in Southeast Asia affected over 3.4 million households in 2018 [88].

Table 8. Current levelised and annual costs of the utilities by source

Utility	Levelised cost	Annual consumption ^a	Annual costs (USD/hh·yr)
Electricity			
Diesel	0.46 USD/kWh	100 kWh/hh·yr	46
Heat for cooking			
LPG	10.21 USD/GJ	1,937 MJ/hh·yr	20
Kerosene	18.11 USD/GJ	215 MJ/hh·yr	4
Charcoal	42.78 USD/GJ	745 MJ/hh·yr	32
Fuel wood	33.65 USD/GJ	1505 MJ/hh·yr	51
Crop residues	6.92 USD/GJ	465 MJ/hh·yr	3
<i>Total^p</i>	<i>22.48 USD/GJ</i>	<i>4,867 MJ/hh·yr</i>	<i>109</i>
Water			
Groundwater	0.80 USD/m ³	129 m ³ /hh·yr	98
Surface water	0.34 USD/m ³	44 m ³ /hh·yr	13
<i>Total local water^p</i>	<i>0.63 USD/m³</i>	<i>173 m³/hh·yr</i>	<i>111</i>
Bottled water (18.9 L) ^c	45.97 USD/m ³	19 m ³ /hh·yr	880
Bottled water (1.5 L) ^c	342.40 USD/m ³	5 m ³ /hh·yr	1797
<i>Total imported water^p</i>	<i>104.49 USD/m³</i>	<i>24 m³/hh·yr</i>	<i>2,677</i>
<i>Total water^p</i>	<i>14.04 USD/m³</i>	<i>197 m³/hh·yr</i>	<i>2,789</i>
Total annual life cycle cost			2,944

^a Based on the functional unit, i.e. annual consumption of 100 kWh electricity, 4.87 GJ heat for cooking and 197 m³ water per household.

^b Based on the share of different fuels and water sources, respectively (see Figure 5 and Figure 6).

^c Purchase cost of imported water.

Figure 8. Annual life cycle costs per household for the current situation and future scenarios

Figure 9. Annualised capital costs per household for the current situation and future scenarios

Figure 10. Operating and maintenance costs per household for the current situation and future scenarios

3.2.2 Environmental sustainability assessment

The total annual environmental impacts of the current synergen system are shown in Figure 11; the breakdown by utility can be found in Tables S1-S3 in the Supplementary Information (SI). In 13 out of the 18 environmental categories, water provision contributes more than half of the total impacts per household (Figure S1). This is primarily due to the production of 1.5 L bottles. Despite being completely sourced from fossil fuels, power consumption contributes only 0.5-13% to the impacts.

The total GWP is estimated at 1.7 t CO₂-eq./hh-yr, with 51% attributed to the water in 1.5-L bottles. At 1 t CO₂-eq./kWh and consumption of 100 kWh/hh-yr, electricity contributes 6% to the total impact of the synergen system. Power required for the water supply (0.23 kWh/m³) adds a further 2.7%. The average GWP of the cooking fuel mix is 142 g CO₂-eq./MJ, with 67% of the impact occurring at the point of use. Fuel processing and collection cause 31% of the GWP of cooking, and the stoves the remaining 2%. Therefore, imported water and cooking fuels are the hotspots for this impact.

The system has a WDP of 10.4 m³/m³ or 2,229 m³/hh-yr. Since a household consumes only 197 m³/yr of water, 91% of WDP is embedded or virtual water. Most of the embedded water is derived from the manufacture of plastic bottles. Looking at each utility, the WDP of electricity is 0.25 m³/kWh while that of heat for cooking is 32 L/MJ. Scaling up to the household level, these only contribute 1% and 7% to the total, respectively.

Figure 11. Annual environmental impacts per household for the current situation and future scenarios

[All impacts are expressed per household per year. BAU: Business as usual; Tran.: Transition; Indep.: Independent. For the impacts nomenclature, see Table 6]

As mentioned above, direct residential consumption of electricity has a relatively small contribution to the impacts. An exception is TAP (13% contribution) due to SO₂ emissions from combustion of diesel. Electricity is also used in local water production, although its impacts are lower than those from imported water. Within the water supply chain, electricity has the highest contributions to POFP (20%) and PMFP (14%).

The cooking fuels are the greatest contributors to PMFP and POFP (80% and 87%, respectively), primarily due to emissions of particulates from combustion of solid biomass fuels (for PMFP) and non-methane volatile organic compounds (NMVOC) from charcoal production. Cooking fuels also cause most of FEP and TETP (61%). Both are mainly due to the disposal of ash from solid biomass fuels to soil.

The water supply contributes >90% to water ecotoxicity (FETP and METP) and land occupation (ALOP and ULOP). These are again due to the bottles, with additional impacts from bottle cleaning (ecotoxicity) and paper labels (land occupation). The impacts of the current situation are discussed further in comparison with the future scenarios in section 3.3.1.2.

3.3 Future scenarios

This section starts with a discussion of the economic sustainability of the future scenarios, providing a breakdown of different costs. This is followed by a detailed discussion of different environmental impacts to determine the environmental sustainability of the future scenarios.

3.3.1 *Economic sustainability assessment*

3.3.1.1 Total life cycle costs (LCC)

As shown in Figure 8 and Table 9, the Independent scenario has the lowest and BAU the highest LCC: 231 and 5,364 USD/hh·yr, respectively. The former is nearly 13 times lower than at present due to the absence of imported fuels and water and reduced levelised costs of electricity (0.10 USD/kWh), cooking fuels (18 USD/GJ) and water (0.67 USD/m³). The non-generating components of the power system, i.e. battery storage and system converter, represent 9% of the total LCC of electricity (0.79 and 0.18 USD/hh·yr, respectively; Table 9).

The BAU scenario has 82% higher LCC than currently. With a forecasted increase in diesel price, as well as higher dependence on diesel power and imported water, the levelised cost of electricity is more than twice as expensive (1.02 USD/kWh) and the levelised cost of water is 85% higher in the BAU scenario than at present (Table 9). It can also be noted that the LCC in the BAU scenario represent 90% of the current national average household income in the Philippines (5,912 USD/yr [24]), making it unsuitable for remote communities.

The LCC in the Transition scenario are 19% lower than the present (2,393 USD/hh·yr), resulting from a 12-76% decrease in levelised costs. Specifically, the cost of electricity reduces to 0.11 USD/kWh, of cooking to 20 USD/GJ and of water to 12 USD/m³ (Table 9). This is largely due to the absence of imported fuels (diesel and LPG) and the adoption of biogas for cooking.

As in the current situation, the water supply is overwhelmingly the main contributor to the total LCC (>95%) in the BAU and Transition scenarios (Figure 8). This is almost solely due to the costs of imported water (95-97%). The water supply also represents the majority (57%) of the costs in the Independent scenario, despite the self-sufficiency in water (and energy).

Therefore, these results suggest that self-sufficient utility systems in remote communities are financially attractive but will require adoption of new technologies, such as seawater desalination, biomass gasification and anaerobic digestion, to replace imported energy and water supply.

Table 9. Levelised and annual costs of the utilities for the future scenarios

Utility	Levelised cost	Annual consumption ^a			Annual costs		
		Business as usual	Transition	Independent	Business as usual	Transition	Independent
Electricity	(USD/kWh)	(kWh/hh·yr)	(kWh/hh·yr)	(kWh/hh·yr)	(USD/hh·yr)	(USD/hh·yr)	(USD/hh·yr)
Diesel	1.02 (BAU) 1.56 (Tran.)	100	0.6	-	101.93	0.88	-
Solar PV	0.08	-	3.8	17.3	-	0.31	1.42
Wind	0.22	-	14.9	11.4	-	3.28	2.49
Biogas	0.26	-	6.1	-	-	1.37	-
Bio-syngas	0.08	-	74.6	71.3	-	5.48	5.40
Li-ion battery ^b	<0.01	n/a	n/a	n/a	-	-	0.79
System converter ^b	<0.01	n/a	n/a	n/a	-	0.01	0.18
<i>Total</i>		<i>100</i>	<i>100</i>	<i>100</i>	<i>101.93</i>	<i>11.33</i>	<i>10.29</i>
Heat for cooking	(USD/GJ)	(MJ/hh·yr)	(MJ/hh·yr)	(MJ/hh·yr)	(USD/hh·yr)	(USD/hh·yr)	(USD/hh·yr)
LPG	22.33	2518	1571	-	56.22	35.09	-
Kerosene	41.70	27	27	-	1.11	1.11	-
Charcoal	24.43	426	602	949	10.40	14.71	23.19
Fuel wood	19.94	860	1215	1916	17.14	24.23	38.21
Crop residues	4.00	266	376	591	1.06	1.50	2.37
Biogas	17.81	737	1041	1375	13.12	18.55	24.48
Electricity	1.87 ^c	35	35	35	12.30	1.42	1.30
<i>Total^c</i>		<i>4867</i>	<i>4867</i>	<i>4867</i>	<i>111.36</i>	<i>96.61</i>	<i>89.55</i>
Water	(USD/m ³)	(m ³ /hh·yr)	(m ³ /hh·yr)	(m ³ /hh·yr)	(USD/hh·yr)	(USD/hh·yr)	(USD/hh·yr)
Groundwater	0.64 ^c	113	113	113	112.39	76.41	76.00
Surface water	0.18	38	38	38	6.98	6.98	6.98
Desalination	0.63 ^c	-	26	46	-	28.77	48.64
<i>Total local water^d</i>		<i>151</i>	<i>177</i>	<i>197</i>	<i>119.37</i>	<i>112.17</i>	<i>131.62</i>
Bottled water (18.9 L) ^e	45.97	36	16	-	1,653.96	714.09	-
Bottled water (1.5 L) ^e	342.40	10	4	-	3,377.77	1,458.35	-
<i>Total imported water^d</i>		<i>46</i>	<i>20</i>	<i>-</i>	<i>5,031.73</i>	<i>2,172.44</i>	<i>-</i>
<i>Total water^d</i>		<i>197</i>	<i>197</i>	<i>197</i>	<i>5151.10</i>	<i>2284.61</i>	<i>131.62</i>
Total annual life cycle cost					5364.39	2392.56	230.78

^a Based on the functional unit, i.e. annual consumption of 100 kWh electricity, 4.87 GJ heat for cooking and 197 m³ water per household.

^b Non-generating components.

^c Excluding the cost of electricity.

^d Based on the share of different fuels and water sources, respectively (see Figure 5 and Figure 6).

^e Purchase cost of imported water.

3.3.1.2 Annualised capital costs (ACC)

Capital expenditure in the future scenarios is 8-21% higher than at present (107 USD/hh·yr), with the Independent scenario having the highest costs (129 USD/hh·yr). Water supply is responsible for 63-75% of the total ACC (Figure 9) and the most significant cost items include the infrastructure for wells, pipes and desalination modules (Table 4). The equivalent capital costs of the power system (25 USD/hh·yr) in the BAU scenario are 53% greater than at present since a proportional increase in generator capacity is needed. Capital costs are also 21% higher in the Independent scenario than currently due to the high costs of solar PV panels and wind turbines. Capital investment for provision of cooking heat at least trebles in the future scenarios, mainly due to the infrastructure for biogas production. In addition, introduction of new fuel types to the mix requires installation of their corresponding stoves.

3.3.1.3 Operating and maintenance costs (OMC)

The Independent scenario has the lowest OMC and BAU the highest: 102 and 215 USD/hh·yr, respectively (Figure 10). The Transition scenario is close to the Independent (105 USD), both of which have significantly lower costs than at present (160 USD). Across the scenarios, more than 59% of the OMC is attributed to cooking due to costs of charcoal and fuel wood. An exception is the BAU scenario where cooking fuels have somewhat lower contribution due to a greater relative influence of the electricity cost. The latter is due to the increased use of diesel, which constitutes 36% of the electricity cost. Electricity used for cooking in the future scenarios is minimal, although it is responsible for 13% of the cooking OMC in the BAU scenario. While the OMC of electricity and cooking are lower in the Transition and Independent scenarios than at present, the OMC for water increases by 1-37%. This is due to the chemicals and electricity used for desalination. The water-energy nexus is also reflected in the economic analysis as electricity contributes 63-89% of the water sector's OMC across all scenarios.

3.3.2 Environmental sustainability assessment

The results of the environmental sustainability assessment for the three scenarios are summarised in Figure 11 in comparison with the current situation; further details for each utility can be found in Tables S1-S3 the SI. The Independent scenario is the best option which has the lowest impacts in 14 categories. By contrast, BAU is the worst alternative with 13 highest impacts. The Transition scenario has the highest TETP, while all future scenarios have better environmental performance in air pollution (PMFP and POFP) and eutrophication (FEP and MEP) than the current situation. Further discussion of the results is provided in the next section.

3.3.2.1 Climate change (GWP)

The BAU scenario has 35% higher GWP than the current situation (2.31 vs 1.71 t CO₂-eq./hh·yr), with 67% of the impact attributed to the water sector due to the increased purchases of bottled water. The Transition and Independent scenarios have 25% and 70% lower GWP than at present. The introduction of renewables in these scenarios, especially bioenergy from gasification and anaerobic digestion, reduces significantly the GWP of power production: by 85% in Transition and >100% in Independent (i.e. net credits for biomass gasification). This also has the effect of reducing the impacts of water supply, which compounded with a lower fraction of water imports, results in 28% and 99% lower GWP for the water sector, respectively.

3.3.2.2 Air pollution (ODP, PMFP, POFP)

Across the scenarios as well as in the current situation, water supply is responsible for the majority of ODP due to the CCl₄ emissions associated with the production of detergents for the cleaning of reusable bottles. PMFP and POFP are mainly due to the combustion of solid biomass fuels used for cooking. The air pollution impacts decrease from their current levels in all future scenarios, except for the ODP in BAU. Generally this is due to an improved cooking fuel mix since biogas benefits from the system credits, reducing the ODP of LPG and high PMFP and POFP of solid biomass fuels. For the BAU, the ODP is 41% higher than at present as all sectors individually see an increase in this impact of 0.5-71%. The PMFP and POFP of electricity and water also increase in BAU by 15-63% because of greater reliance on diesel and imported water, but are compensated by the 56-61% reductions from the cooking system resulting from a lower fraction of solid biomass. The net effect is a reduction of 39-43% compared to the current situation. Also, since BAU has the

lowest share of solid biomass in the cooking fuel mix, it has the lowest PMFP and POFP (7.8 and 25 kg NMVOC/hh·yr, respectively).

3.3.2.3 Eutrophication and acidification (FEP, MEP, TAP)

Like the previous impacts, eutrophication (FEP and MEP) is lower in the three future scenarios than at present, with net-negative impacts across the scenarios, except for MEP in the BAU which is slightly net-positive. This is driven by significant system credits related to anaerobic digestion for avoided disposal of animal manure and the use of the digestate as a fertiliser substitute. The Independent scenario has the lowest MEP while the Transition is the best option for FEP.

For acidification, LPG and imported water have high contributions to TAP from the upstream petrochemical stage in oil refining and bottle production. Hence, TAP is lower in the Transition and Independent scenarios where there is reduced consumption of LPG and imported water. This impact is net-negative for the Independent scenario due to the credits for utilisation of manure for biogas used for cooking. By the same logic, the TAP of the BAU scenario is 24% higher than the current impact due to higher share of LPG and imported water.

3.3.2.4 Ecotoxicity (FETP, METP, TETP)

FETP and METP are 63% higher in the BAU scenario than presently (105 and 87 vs 65 and 54 kg 1,4-DB eq./hh·yr, respectively), with 96% of the impacts derived from the water supply. The higher amount of imported water in this scenario leads to additional ecotoxicity associated with the production and cleaning of bottles. The water supply is also the highest contributor to FETP and METP in the Transition and Independent scenarios, although in this case the biogas and bio-syngas credits reduce the total impacts to a net 69% (Transition) and 2% (Independent) compared to the current situation.

On the other hand, TETP is 2-10% higher in the future scenarios than at present. Water supply is the most significant contributor in the BAU scenario due to imported water, with a 69% higher impact than of the current water supply, mostly due to plastics manufacture. The Transition scenario has more than five times higher TETP per kWh than the current situation due to heavy metals in the ash from crop residues and digestate from anaerobic digestion. Lastly, the electricity and cooking fuel mix in Independent increase TETP by 5%, also due to ash and digestate.

3.3.2.5 Resource depletion (FDP, MDP, WDP)

BAU would lead to the highest increase in resource depletion on the current situation (47-61%) while the Independent scenario would reduce the resource dependence by >78%. FDP would also be net-negative, avoiding depletion of 7 kg oil eq./hh·yr due to the credits for the displacement of mineral fertilisers by digestate.

The Transition scenario benefits from the lower usage of LPG, kerosene and imported water as well as the credits for waste biomass-derived energy. As a result, it has 21-39% lower impacts relative to the present depletion of resources.

3.3.2.6 Land use (ALOP, NLTP, ULOP)

Land transformation and occupation in the future scenarios follow the trend of most of the previous categories: the BAU has impacts higher than the present day, while the Transition and Independent scenarios result in progressively lower impacts. The latter scenario has a net-negative ULOP, avoiding the use of 3.5 m² annually. However, this trend is different if only electricity is considered. In the Transition scenario, electricity supply has the lowest impacts, with all three categories having net credits for waste biomass utilisation, while land occupation is higher in the Independent scenario due to the space required to install solar PV panels. However, credits from biomass gasification in the Independent scenario still lead to a net reduction in ULOP of 26% relative to the current situation.

3.3.2.7 Human health (HTP, IRP)

The BAU scenario has the highest HTP and IRP, with the impacts of electricity and water supply increasing by 11-72% compared to the current situation. However, the BAU cooking fuel mix has 54% lower HTP per MJ due to lower fractions of solid biomass. Independent is again the best

option for both impacts. More than 62% of the impacts in all the scenarios are attributed to the water supply, except for HTP of the Independent scenario. In this case, the absence of imported water shifts the majority of the HTP contribution to the cooking fuels.

4. Conclusions and recommendations

This paper has quantified the economic and environmental sustainability of supplying electricity, cooking heat and water to remote communities. Both the current situation and future scenarios have been evaluated following the synergen approach developed in this work to consider synergistic interactions between the three utilities.

The current annual LCC are estimated at 2,944 USD per household, with 91% due to the imported water. The highest costs are found for BAU (5,364 USD/hh·yr), followed by the Transition scenario (2,393 USD/hh·yr), also largely due to the imported water. The Independent scenario demonstrates that a remote community can be fully sufficient in its utilities with an order of magnitude lower costs than at present (231 USD/hh·yr). However, capital investment for an independent off-grid utility system is 21% greater than today. This can pose a barrier for developing countries as investors may demand higher rates of returns to reflect the risks associated with lack of experience and instability of energy policies, as well as perceptions of technology immaturity. This risk may be mitigated through involvement of local stakeholders, demonstration of environmental and societal benefits and through appropriate policy incentives.

The Independent scenario has the lowest impacts in 14 categories while BAU is the worst alternative for 13 impacts. The Transition scenario has the highest TETP, while all future scenarios have lower PMFP and POFP and eutrophication than at present. Overall, there is no single scenario wherein all of the environmental impacts and costs are reduced compared to the current situation. However, the Transition and Independent scenarios have lower impacts than at present in almost all environmental categories and lower LCC.

The combined analysis of the three utilities carried out in this study further suggests that seawater desalination and bioenergy from residual/waste biomass can enable a sustainable transition towards self-sufficiency of remote communities as seen in the Independent scenario. Although desalination can replace imported bottled water, its sustainability is dependent on the power system that runs it. Hence, proposals for implementing desalination in remote communities are recommended to evaluate the local power system to ensure that environmental impacts are reduced. Desalination can also operate in synergy with variable renewable energy sources (e.g. solar PV and wind) to utilise excess power generated at off-peak times. While the results of this work have been obtained through hourly simulations, future work can validate these results through pilot demonstrations or integrated analysis with control systems.

Moreover, a reliable supply of waste biomass, such as crop residues and animal manure, is necessary to realise the economic and environmental benefits they offer. If bioenergy is adopted as a main source of electricity and heat for cooking in remote communities, appropriate management of the agricultural production cycle will be required to allocate biomass resources to different utility sectors. Further work is needed to determine how much of these resources are realistically harvestable on a sustainable basis. As biomass is a versatile resource for agricultural communities, supply chain optimisation can provide guidance on its optimal utilisation as a fuel, food or agricultural input.

Additionally, high dependence on a specific technology or resource can pose risks in security of supply that can affect other sectors. To broaden the sustainability assessment, consideration of energy security and other social indicators is recommended for future work. Furthermore, the synergen approach applied here could be applied to explore the sustainability implications for other climatic zones, production scales and technology options. Future studies could also investigate the application of multi-criteria decision analysis to facilitate further understanding and trade-offs between benefits and costs of future synergen systems in remote communities.

Finally, it is recommended that community planners and local authorities should consider other aspects of household consumption in addition to electricity when devising sustainability strategies. As shown in this study, traditional cooking fuels and imported water can be greater sources of environmental impacts and costs than power generation. Development pathways that rely on currently installed technologies and supply chains (e.g. the BAU scenario) can exacerbate these impacts while increasing life cycle costs. Although new technologies may be more capital-intensive, local stakeholders can use life cycle approaches to demonstrate lower life cycle costs and encourage investment in remote communities.

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**Synergistic generation of energy and water in remote communities:
Economic and environmental assessment of current situation and future scenarios**

Jhud Mikhail Aberilla, Alejandro Gallego-Schmid, Laurence Stamford and Adisa Azapagic

Supplementary Information

Nomenclature

1,4-DB	1,4-dichlorobenzene
ALOP	agricultural land occupation potential
eq.	equivalent
FDP	fossil depletion potential
FEP	freshwater eutrophication potential
FETP	freshwater ecotoxicity potential
GWP	global warming potential
HTP	human toxicity potential
IRP	ionising radiation potential
m2a	m ² year
MDP	mineral depletion potential
MEP	marine eutrophication potential
METP	marine ecotoxicity potential
NLTP	natural land transformation potential
NMVOC	non-methane volatile organic compounds
ODP	ozone depletion potential
OMC	operating and maintenance costs
PM10	particulate matter (<10 µm)
PMFP	particulate matter formation potential
POFP	photochemical oxidant formation potential
TAP	Terrestrial acidification potential
TETP	terrestrial ecotoxicity potential
ULOP	urban land occupation potential
WDP	water depletion potential

Table S1. Life cycle environmental impacts of electricity for the current situation and future scenarios

Annual impact per household^a	Current situation	Business as usual	Transition	Independent
GWP (kg CO ₂ eq.)	100.9	115.5	15.4	-0.4
ODP (mg CFC-11 eq.)	18.8	21.6	-0.6	-0.1
PMFP x10 (g PM ₁₀ eq.)	58.2	66.7	-3.3	0.4
POFP x100 (g NMVOC)	17.5	20.0	0.3	0.3
FEP x10 (g P eq.)	0.3	0.4	-39.9	0.02
MEP x10 (g N eq.)	6.3	7.2	-35.6	0.1
TAP x10 (g SO ₂ eq.)	108.7	124.3	-23.9	1.5
FETP x10 (g 1,4-DB eq.)	92.8	98.7	-29.5	3.0
METP x10 (g 1,4-DB eq.)	77.9	82.9	-24.6	2.6
TETP (g 1,4-DB eq.)	9.1	10.5	49.5	44.3
FDP (kg oil eq.)	34.0	39.0	-1.6	-0.4
MDP x100 (g Fe eq.)	10.4	10.7	0.4	5.7
WDP (m ³)	24.9	26.7	-5.2	4.2
ALOP (dm ² a)	98.1	110.3	-14.0	-3.5
NLTP x10 (cm ²)	23.9	27.5	-0.5	0.3
ULOP x0.1 (m ² a)	1.8	2.0	-4.9	1.3
HTP x10 (g 1,4-DB eq.)	743.1	821.2	701.1	936.7
IRP x100 (g U ²³⁵ eq.)	83.0	95.3	-4.2	-0.6

^a For the acronyms, see the Nomenclature section.

Table S2. Life cycle environmental impacts of cooking heat the current situation and future scenarios

Annual impact per household ^a	Current situation	Business as usual	Transition	Independent
GWP x10 (kg CO ₂ eq.)	69.2	64.4	60.2	50.5
ODP (mg CFC-11 eq.)	72.7	73.1	43.1	-4.0
PMFP x100 (g PM ₁₀ eq.)	102.6	39.7	76.5	97.3
POFP (kg NMVOC)	38.6	17.2	25.9	34.6
FEP x100 (g P eq.)	4.2	-18.6	-27.2	-34.0
MEP x100 (g N eq.)	0.7	-17.8	-26.6	-33.8
TAP x100 (g SO ₂ eq.)	19.6	3.2	-9.3	-13.9
FETP x100 (g 1,4-DB eq.)	52.0	34.7	22.3	0.6
METP x100 (g 1,4-DB eq.)	43.9	28.9	19.2	1.5
TETP x10 (g 1,4-DB eq.)	26.5	16.3	24.2	30.7
FDP (kg oil eq.)	135.9	135.8	79.3	-9.0
MDP (kg Fe eq.)	18.7	21.5	18.5	13.5
WDP (m ³)	154.9	158.2	111.3	40.2
ALOP x0.1 (m ² a)	42.2	39.9	27.4	-1.3
NLTP x10 (cm ²)	105.2	106.8	61.7	-8.5
ULOP (m ² a)	0.8	-1.5	-2.8	-4.1
HTP x10 (kg 1,4-DB eq.)	30.8	14.1	20.5	23.9
IRP (kg U ²³⁵ eq.)	30.5	29.8	17.3	-2.3

^a For the acronyms, see the Nomenclature section.

Table S3. Life cycle environmental impacts of water for the current situation and future scenarios

Annual impact per household ^a	Current situation	Business as usual	Transition	Independent
GWP x100 (kg CO ₂ eq.)	9.2	15.5	6.6	0.1
ODP x10 (mg CFC-11 eq.)	11.4	19.6	8.2	0.1
PMFP x100 (g PM ₁₀ eq.)	19.2	31.3	11.8	0.4
POFP x100 (g NMVOC)	39.8	62.7	23.8	1.1
FEP x10 (g P eq.)	26.7	46.2	-39.4	0.4
MEP x100 (g N eq.)	10.5	17.7	2.0	0.1
TAP x100 (g SO ₂ eq.)	53.0	88.2	32.3	1.2
FETP (kg 1,4-DB eq.)	58.5	100.8	42.5	0.8
METP (kg 1,4-DB eq.)	48.5	83.6	35.2	0.7
TETP x10 (g 1,4-DB eq.)	16.0	27.0	18.5	10.4
FDP x10 (kg oil eq.)	35.3	59.2	23.9	0.2
MDP (kg Fe eq.)	45.7	76.9	33.4	3.7
WDP x100 (m ³)	20.5	33.9	15.4	1.9
ALOP (m ² a)	49.4	83.2	34.1	0.5
NLTP (dm ²)	9.0	14.9	5.8	0.1
ULOP (m ² a)	8.4	14.3	5.4	0.5
HTP x10 (kg 1,4-DB eq.)	51.8	89.3	39.1	2.9
IRP x10 (kg U ²³⁵ eq.)	7.8	13.3	5.5	0.1

^a For the acronyms, see the Nomenclature section.

Figure S1. Annual environmental impacts and levelised cost per household for the current situation
 [Data labels represent total cradle-to-grave impacts. For the acronyms, see the Nomenclature section]