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An integrated sustainability assessment of synergistic supply of energy and water in remote communities

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\textbf{Abstract}

The success of deploying energy and water technologies in remote communities in developing countries can be improved by considering their synergistic relationships and their social, economic and environmental implications. This paper first evaluates social implications of current energy and water supply in a prototypical remote community against five future (2030) scenarios for synergistic provision of electricity, heat for cooking and water. This is followed by an integrated assessment of the social, environmental and economic life cycle sustainability through multicriteria decision analysis. The Business-as-usual (BAU) scenario shows high life cycle health impacts but low impacts from local air pollution. The contrary is true for the Independent and Advanced Independent scenarios which assume community self-sufficiency in energy and water supply. Greater access to electricity and water in the Advanced and Advanced Independent scenarios increases the potential for human development and security of supply, but there is an increase in the risk of accidents and decrease in social acceptability of the water supply. Similarly, a transition towards clean cooking fuels away from traditional solid biomass reduces local air pollution but increases reliance on imported fuels (BAU and Advanced scenarios). The Transition scenario is socially the most sustainable option, while Independent and Advanced Independent are the best options environmentally. They also have the lowest total operating costs, but have higher capital requirements than most other scenarios. Overall, unless extreme preferences for either environmental or social aspects are adopted, the Transition and Independent scenarios emerge as the most sustainable options. This suggests that current energy and water supply to remote communities can be transitioned sustainably to a self-sufficient system that does not depend on imported resources. The scenarios developed in this work present a framework for an integrated design and evaluation of energy and water supply in remote communities with the aim of aiding stakeholders in defining sustainable transition pathways.

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\section{1. Introduction}

According to the United Nations’ Sustainable Development Goals (SDGs) (\textit{UNDP}, 2017), clean energy and water should be universally accessible by 2030. Although there has been a growth in renewable energy, clean cooking and water access, progress is slow and meeting the SDG goals by 2030 will be difficult if not impossible (\textit{International Energy Agency et al.}, 2019; \textit{WHO} and \textit{UNICEF}, 2017). Key recommendations for improving progress include data-based decision support, private financing and removing barriers to social acceptability (\textit{International Energy Agency et al.}, 2019).

Social issues surrounding renewable energy sources for electricity, cooking and water supply have been discussed extensively in literature (\textit{e.g. Berka and Creamer}, 2018; \textit{Sheikh et al.}, 2016) and many studies have considered social sustainability indicators together with techno-economic and environmental criteria (\textit{e.g. Kumar et al.}, 2017; \textit{Mardani et al.}, 2015). Common criteria used to assess the social sustainability of energy and water systems include job creation, public acceptance, health and safety, and security. Social life cycle assessment (SLCA) has been used to determine the social sustainability of energy and water supply and identify hotspots. For example, a study on renewable energy technologies in Malaysia identified labour conditions as the greatest

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Nomenclature

\[ \text{ACC}_S \] annualised capital costs per household for the current situation or scenario \( s \) (USD/hh-year)

\[ \text{BW}_s \] total percentage of bottled water in the current situation or scenario \( s \) (%)

\[ \text{CBW}_s \] annual costs of imported bottled water in the current situation or scenario \( s \) (USD/hh-year)

\[ \text{CC}_t \] capital costs of technology \( t \) in the current situation or scenario \( s \) (USD)

\[ \text{CF}_t \] total percentage of clean cooking fuels in the current situation or scenario \( s \) (%)

\[ \text{C}_t \] capacity of technology \( t \) in the current situation or scenario \( s \) (MW or Mm\(^3\))

\[ \text{DE}_s \] direct employment in the current situation or scenario \( s \) (jobs)

\[ \text{DE}_{w,t} \] direct employment for water technology/source \( t \) in the current situation or scenario \( s \) (jobs)

\[ \text{EF}_{r,t} \] employment factor for fuel supply for technology \( t \) (jobs/PJ)

\[ \text{EF}_{OM,t} \] employment factor for operation and maintenance of technology \( t \) (jobs/MW or jobs/Mm\(^3\))

\[ \text{EG}_s \] annual electricity generation by technology \( t \) in the current situation or scenario \( s \) (TWh/year)

\[ \text{E}_s \] electricity consumption in the current situation or scenario \( s \) (kWh/year)

\[ \text{E}_{ks,s} \] excess electricity generated in the current situation or scenario \( s \) (kWh/year)

\[ \text{FC}_t \] annual fixed costs of technology \( t \) in the current situation or scenario \( s \) (USD/year)

\[ \text{fC}_t \] fuel costs of technology \( t \) in the current situation or scenario \( s \) (USD/year)

\[ \text{FE}_s \] total number of fatalities related to electricity generation in the current situation or scenario \( s \) (no./year)

\[ \text{f}_{t,s,i} \] flow of substance \( i \) to the environment associated with technology/utility source \( t \) in current situation or scenario \( s \) (kg/year)

\[ \text{FR}_t \] fatality rate for technology \( t \) (no./TWh or no./1000 worker-year)

\[ \text{F}_{t,s} \] annual fuel consumption by technology \( t \) in the current situation or scenario \( s \) (PJ)

\[ \text{FW}_s \] total number of fatalities related to water in the current situation or scenario \( s \) (no./year)

\[ \text{HDI}_s \] human development index in the current situation or scenario \( s \) (-)

\[ \text{Hi}_s \] Shannon equitability index of utility \( u \) (electricity, cooking heat or water) in the current situation or scenario \( s \) (-)

\[ i \] substance contributing to impacts category \( m \)

\[ \text{IM}_s \] human health impact potential of impact category \( m \) in the current situation or scenario \( s \) (kg 1,4-DB eq./year for HTP; kg U\(^{235}\) eq./year for IRP; disability-adjusted days (DALY)/year for LAP)

\[ \text{L} \] set of local technology and resource options

\[ m \] impact category

\[ \text{N}_{hn,s} \] number of households (with four persons) in the current situation or scenario \( s \) (no.)

\[ \text{n}_t \] lifetime of technology \( t \) (year)

\[ \text{OMC}_s \] operating and maintenance costs per household for the current situation or scenario \( s \) (USD/hh-year)

\[ \text{P}_{f,s} \] fraction of clean cooking fuel \( cf \) in the current situation or scenario \( s \) (-)

\[ \text{P}_{f,t} \] fraction of fuel \( f \) in the cooking fuel mix in the current situation or scenario \( s \) (-)

\[ \text{P}_{t,s} \] fraction of supply from technology/source \( t \) in the current situation or scenario \( s \) (-)

\[ Q_{m,i} \] characterisation factor of substance \( i \) for category \( m \) (kg/kg)

\[ r \] discount rate (-)

\[ S \] number of scenarios (5), plus the current situation

\[ SC_s \] overall safety of the cooking fuel mix in the current situation or scenario \( s \) (-)

\[ S_{u,t,s} \] supply independence of utility \( u \) in the current situation or scenario \( s \) (-)

\[ SR_{t,u} \] safety score of cooking fuel \( f \) (-)

\[ t \] technology/utility source

\[ U \] total number of supply options for utility \( u \) (no.)

\[ VC_{t,s} \] annual variable costs of technology \( t \) in the current situation or scenario \( s \) (USD/year)

\[ \text{P}_{f,s} \] fraction of clean cooking fuel \( cf \) in the current situation or scenario \( s \) (-)

\[ \text{P}_{f,t} \] fraction of fuel \( f \) in the cooking fuel mix in the current situation or scenario \( s \) (-)

\[ \text{P}_{t,s} \] fraction of supply from technology/source \( t \) in the current situation or scenario \( s \) (-)

\[ Q_{m,i} \] characterisation factor of substance \( i \) for category \( m \) (kg/kg)

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\[ t \] technology/utility source

\[ U \] total number of supply options for utility \( u \) (no.)

\[ VC_{t,s} \] annual variable costs of technology \( t \) in the current situation or scenario \( s \) (USD/year)

Source of adverse social impacts (Takeda et al., 2019). SLCA has also been combined with life cycle assessment (LCA) to determine both the social and environmental impacts of water but focusing on urban water supply (e.g. García-Sánchez and Guereca, 2019). Social impact assessment (SIA) can also be used to anticipate the effects on local stakeholders of proposed energy and water development projects (Vanclay et al., 2015). However, weak coherence between the studied impacts and the local stakeholders’ concerns typically found in SIA studies can ultimately result in failed projects (Colvin et al., 2019; Larsen et al., 2018). The importance of stakeholder concerns and other social aspects for the success of energy and water development projects has been highlighted by several authors (e.g. Almeshqab and Ustun, 2019; Berka and Creaver, 2018). However, lack of data, especially for developing regions, can limit the extent of social sustainability assessments (Lehmann et al., 2013).

Nevertheless, it is important to understand not only social, but also environmental and economic implications of proposed development projects. This requires a systems approach underpinned by life cycle thinking to help identify trade-offs between the sustainability criteria and avoid unintended consequences (Azapagic and Perdan, 2014). Since this is a multicriteria problem, multicriteria decision analysis (MCDA) is an appropriate framework for integrating the three sustainability domains (Cinelli et al., 2014; Diaz-Balteiro et al., 2017; Janeiro and Patel, 2015). A key advantage for this integration is the ability to evaluate both quantitative (environmental and economic) with qualitative (social) criteria. MCDA also helps to improve understanding and resolution of the sustainability problem by promoting stakeholder engagement and consensus (Azapagic et al., 2016; Campos-Guzmán et al., 2019).

Literature reviews on the application of MCDA in sustainability assessment highlight the breadth of application across different sectors (Diaz-Balteiro et al., 2017) but also the prevalence of studies based in developed countries (Bhardwaj et al., 2019; Kumar et al., 2017). For example, the use of electrification and energy transition scenarios with MCDA for developing and remote communities has been analysed for the cases of Austria (Kowalski et al., 2009), Colombia (Rosso-Cerón et al., 2019), Bangladesh (Rahman et al., 2013), Finland (Väisänen et al., 2016), Germany (McKenna et al., 2018), Philippines (Ocon et al., 2018), Switzerland (Trutnay et al., 2011), and Venezuela (Rojas-Zerpa and Yusta, 2015). Despite different sustainability criteria, weighting schemes and MCDA methods, all the studies show that integration of multiple technologies into hybrid systems leads to
better sustainability performance due to the balance between conflicting criteria (McKenna et al., 2018; Ocon et al., 2018; Rojas-Zerpa and Yusta, 2015; Rosso-Cerón et al., 2019). Linking scenario development with MCDA has also been suggested to help explore a range of possible outcomes with the aim of improving stakeholder understanding of the implications of proposed projects (Trutnevyte et al., 2011).

Opportunities to address multiple SDGs, including climate mitigation and economic growth, can be found in the synergies within the energy-water nexus (Bieber et al., 2018). Previous work by the authors of this paper has demonstrated the feasibility of synergistic generation (termed here “synergen”) as an approach to integrate planning of provision of electricity, heat for cooking, and water in remote communities (Aberilla et al., 2020a). This paper furthers the development of the synergen approach for sustainable planning in remote communities through a comprehensive integrated assessment of the social, environmental and economic sustainability of energy and water systems working in synergy with each other. Furthermore, this work demonstrates a novel multidisciplinary approach to community development by integrating energy systems design, techno-economic analysis, LCA, SIA and MCDA.

The objectives of the study are (1) to develop indicators and evaluate the social sustainability of electricity, heat for cooking and water supply in remote communities; (2) to integrate the social sustainability with the environmental and economic dimensions through MCDA; (3) to quantify and compare the overall sustainability of the current situation with a range of future synergen scenarios, assuming a prototypical remote community. A life cycle approach is followed for the evaluation of the environmental and economic sustainability as well as the social sustainability where feasible, as detailed in the next sections.

2. Methodology

The methods used in this paper build upon the authors’ previous work (Aberilla, 2020; Aberilla et al., 2020b, 2020c, 2020a, 2019) which evaluated the life cycle environmental and techno-economic sustainability of integrated energy and water systems for remote communities, considering the current situation and three future scenarios. An overview of these, as well as of two further scenarios developed as part of this work, is presented below. The social sustainability indicators used for the social sustainability assessment are detailed in Section 2.2. This is followed in Section 2.3 by a brief overview of the methods used for the environmental and economic sustainability assessment. The MCDA method selected for the overall sustainability evaluation of the energy and water synergen systems is described in Section 2.4.

2.1. Current situation and future scenarios

The synergen system coupling energy and water supply considered in the study is depicted in Fig. 1. It comprises a range of electricity sources, cooking fuels and water supply options, that are either used currently in remote communities or could be deployed in the future.

To provide a context, a remote off-grid community typically found in developing countries is considered in the study. Specifically, small-island communities in the Philippines are taken as representative of such off-grid communities (Bertheau and Blechinger, 2018). The assumed size of community is 4534 households, comprising on average four persons. The current annual demand per household is 100 kWh of electricity (Angelou et al., 2013), 4.87 GJ of heat for cooking (Philippine Statistics Authority, 2013) and 197 m$^3$ of water (World Bank, 2006). The current mix of electricity, cooking heat and water supply is summarised in Table 1. All utilities are supplied locally, except for diesel, LPG, kerosene and bottled water which are imported from outside the community.

The five future scenarios mentioned above are defined for the year 2030, to coincide with the time horizon for SDGs. By then, the community is expected to grow to 5588 households (Philippine Statistics Authority, 2016). Three of the scenarios are based on the current demand for energy and water (Aberilla et al., 2020a); business as usual (BAU), Transition and Independent (Table 1). The BAU scenario considers only currently-used technologies, while the Transition uses new options for additional capacity development, shown in Table 1. The Independent scenario is constructed such that the community does not consume imported fossil fuels and bottled water. In these scenarios, the total annual demand in the community is 27.2 TJ of energy for cooking and 1.10 Mm$^3$ of water.

In light of the relationship between access, development and consumption (Wang et al., 2015), two further scenarios have been defined as part of this work to reflect the potential increase

![Fig. 1. Synergistic generation (“synergen”) of energy and water in remote communities.](image-url)
in household demand for energy and water. The Advanced scenario sees the electricity demand go up to 365 kWh/year due to the use of appliances, such as refrigerators (Bhattia and Angelou, 2015). Water use also increases to match the national average of 260 m$^3$/year (FAO, 2011), resulting in a greater community demand of 1.45 Mm$^3$/year. Energy demand for cooking is assumed to remain the same as in the previous three scenarios (4.87 GJ of heat/hh-year), although a full transition to clean cooking is assumed in this scenario through the phasing out of traditional solid biomass fuels. The final scenario – Advanced Independent – represents a combination of the increased demand in the Advanced scenario and the phasing out of imported fossil fuels and water bottled in Independent.

The electricity supply systems in all the scenarios have been designed and optimised on costs through HOMER Pro (HOMER Energy LLC, 2017) (Table 2), based on the techno-economic parameters detailed in Tables S1 and S2 in the Supplementary Information (SI). Considerations for the environmental and social aspects are included through the technology and resource constraints that form part of the scenario definitions above. To achieve the clean cooking fuel mix as defined in the Advanced scenario, solid biomass fuels are replaced by liquefied petroleum gas (LPG). The cooking fuel mix in the Advanced Independent scenario follows that of the Independent scenario, although with a higher share of electric stoves (proportional to the increase in electricity use), replacing some solid biomass fuels (Table 1). For the water supply mix, desalination is assumed to provide the additional water demand in both Advanced and Advanced Independent scenarios due to groundwater and surface water resources already being exploited to the maximum sustainable extent (Aberilla, 2020) (Table 1). As seen in Table 2, the cooking fuels and water supply mixes increase electricity requirements for the community beyond the values estimated for direct residential consumption.

2.2. Social sustainability assessment

The social sustainability of the energy and water supply scenarios in this study is evaluated based on a variety of criteria and

| Table 1 | Energy and water supply mix in the current situation and future scenarios. |
|---------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Utility | Current situation | Business as usual | Transition | Independent | Advanced | Advanced Independent |
|---------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Electricity, excluding cooking (kWh/hh-year) | 100 | 100 | 100 | 100 | 321 | 321 |
| Diesel (%) | 100 | 100 | 1 | - | 1 | - |
| Solar (%) | - | - | - | 22 | - | 18 |
| Wind (%) | - | - | 16 | 12 | - | - |
| Biogas (%) | - | - | 6 | 0 | 0 | - |
| Bio-syngas (%) | - | - | 74 | 67 | 99 | 82 |
| Cooking (MJ/hh-year) | 4867 | 4867 | 4867 | 4867 | 4867 | 4867 |
| Biogas (%) | - | 15 | 21 | 28 | 28 | 28 |
| Electricity (%) | - | 1 | 1 | 1 | 3 | 3 |
| Charcoal (%) | 15 | 9 | 12 | 20 | - | 17 |
| Fuel wood (%) | 31 | 18 | 25 | 39 | - | 35 |
| LPG (%) | 40 | 52 | 32 | - | 69 | - |
| Kerosene (%) | 4 | - | 1 | 1 | - | - |
| Crop residues (%) | 10 | 5 | 8 | 12 | - | 16 |
| Water (m$^3$/hh-year) | 197 | 197 | 197 | 197 | 260 | 260 |
| Ground (%) | 65 | 57 | 57 | 57 | 43 | 43 |
| Surface (%) | 22 | 20 | 20 | 20 | 15 | 15 |
| Desalinated (%) | - | - | 13 | 23 | 34 | 42 |
| Bottled (18.9 L) (%) | 10 | 18 | 8 | - | 6 | - |
| Bottled (1.5 L) (%) | 3 | 5 | 2 | - | 2 | - |

*All utilities are supplied locally, except for diesel, LPG, kerosene and bottled water which are imported from outside the community.*

| Table 2 | Electricity demand and component sizing of the electricity system in the current situation and future scenarios. |
|---------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Item | Current situation | Business as usual | Transition | Independent | Advanced | Advanced Independent |
|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Demand | | | | | | |
| Number of households | 4534 | 5588 | 5588 | 5588 | 5588 | 5588 |
| Residential load (kWh/hh-year)$^d$ | 100 | 112 | 112 | 112 | 365 | 365 |
| Households with electricity (%) | 50 | 100 | 100 | 100 | 100 | 100 |
| Total residential load (MWh/year) | 226.7 | 625.9 | 625.9 | 625.9 | 2039.6 | 2039.6 |
| Power for local water production (MWh/year) | 205.4 | 221.7 | 828.8 | 1289.2 | 2258.0 | 2716.2 |
| Total electrical demand (MWh/year) | 432.1 | 847.6 | 1454.7 | 1915.1 | 4297.6 | 4755.8 |
| System components | | | | | | |
| Diesel generators (kW) | 100 | 300 | 100 | - | 100 | - |
| Solar PV (kWp) | - | - | 35.7 | 214 | - | 604 |
| Wind turbine (kW) | - | - | 100 | 100 | - | - |
| Gas turbine, anaerobic digestion (kW) | - | - | 50 | - | - | - |
| Gas turbine, biomass gasifier (kW) | - | - | 200 | 300 | 650 | 650 |
| Li-ion battery (kWh) | - | - | - | 194 | 126 | 1256 |
| System converter (kW) | - | - | 10 | 179 | 90.5 | 171 |
| Generation mix (MWh/year) | 432.1 | 897.8 | 1478.3 | 1940.5 | 4306.0 | 4991.3 |
| Diesel | 432.1 | 897.8 | 8.3 | - | 46.9 | - |
| Solar | - | - | 56.0 | 336.1 | - | 90.6 |
| Wind | - | - | 220.2 | 220.2 | - | - |
| Bio-syngas | - | - | 1103.3 | 1384.2 | 4259.1 | 4089.7 |

*Previously reported in Aberilla et al. (2020a).*  
*Developed in this work; see Section 2.3 for details.*  
*Includes electricity for cooking.*
indicators that have been used for decision support in energy and water planning (Mardani et al., 2015; Wang et al., 2009). In selecting an appropriate set of indicators, it is recommended to consider consistency with the objectives, independency and measurability of indicators (Marinakis et al., 2017; Wang et al., 2009). To this end, six issues have been identified for consideration in this study (Table 3): human health, job creation, safety, security of supply, use of local resources and social acceptability. In total, 16 social sustainability indicators are considered across these six issues. The motivation for their selection and their definitions are detailed in the next sections.

2.2.1. Human health

The issue of human health and safety is a widely recognised area of protection in society (Goedkoop et al., 2013). Many life cycle impact assessment methods, such as ReCiPe (Goedkoop et al., 2013), already include human health impacts which are commensurate with the life cycle approach taken in this study. Therefore, human toxicity and ionising radiation potentials (HTP and IRP, respectively) are categorised as social impacts based on the ReCiPe method. In addition, direct emissions which contribute to particulate matter and smog formation have damage pathways that occur locally and in short time horizons (van Zelm et al., 2016). Hence, the human health impacts of local emissions contributing to these local air pollution (LAP) categories are included as human health indicators. Characterisation factors are used to translate environmental flows into health impacts for the above three impact categories as follows:

\[
I_{m,s} = \sum_{i}^{m} \sum_{t,s}^{S} \frac{Q_{m,i}}{f_{i,t,s}}
\]

where:

- \(I_{m,s}\) human health impact potential of impact category \(m\) in the current situation or scenario \(s\) (kg 1,4-DB eq./year for HTP; kg U²³⁵ eq./year for IRP; disability-adjusted life years (DALY)/year for LAP)
- \(Q_{m,i}\) characterisation factor of substance \(i\) for category \(m\) (kg/kg)
- \(f_{i,t,s}\) flow of substance \(i\) to the environment associated with technology/utility source \(t\) in current situation or scenario \(s\) (kg/year)
- \(m\) impact category
- \(i\) substance contributing to impacts category \(m\)
- \(t\) technology/utility source
- \(S\) number of scenarios (5), plus the current situation.

Standard characterisation factors in ReCiPe 1.08 (Goedkoop et al., 2013) have been used for HTP and IRP, while regionalised factors for the Philippines (van Zelm et al., 2016) have been applied to estimate local health impacts of air pollution.

2.2.2. Job creation

Employment is considered a key social and political indicator, especially in energy systems planning (Campos-Guzmán et al., 2019; Sheikh et al., 2016; Stamford and Azapagic, 2012). Given that the primary context for this study is related to local stakeholders in remote communities, direct employment is chosen as the indicator for local job creation. The total direct employment generation potential is estimated as the sum of jobs expected in operation and maintenance, and jobs associated with fuel supply:

\[
DE_s = \sum_{t \in S} EF_{OM,t} \times C_{t,s} + \sum_{t \in S} EF_{F,t} \times F_{t,s}
\]

where:

- \(DE_s\) direct employment in the current situation or scenario \(s\) (jobs)
- \(EF_{OM,t}\) employment factor for operation and maintenance of technology \(t\) (jobs/MW or jobs/Mm³)
- \(C_{t,s}\) capacity of technology \(t\) in the current situation or scenario \(s\) (MW or Mm³)
- \(EF_{F,t}\) employment factor for fuel supply for technology \(t\) (jobs/PJ)
- \(F_{t,s}\) annual fuel consumption by technology \(t\) in the current situation or scenario \(s\) (PJ).

Direct employment has been estimated using employment factors available in the literature. Jobs during construction of energy and water supply systems are assumed to be performed by external agents and are assumed to be less important for consideration of the local stakeholders. Hence, these are not included in the study. Also, it is assumed that no new jobs are created for the collection of residual biomass fuels (crop residues and animal manure; Table 1) as this is already carried out by waste collectors. For desalination, there are no published systematic compilations of employment factors but individual reports (El-Sheikh et al., 2010; ISI Water, n.d.; Poseidon Water, n.d.; San Diego County Water Authority, 2019; Sinclair et al., 2011; Victoria State Government, 2018) indicate strong dependence of employment factors on plant capacity. Therefore, a regression analysis of published values (Fig. 2) has been used to estimate direct employment in desalination plants. The direct employment factors for the energy and water supply systems are summarised in Table 4.

2.2.3. Safety

Worker and end-user safety are one of the most important issues commonly considered in sustainability assessments (Campos-Guzmán et al., 2019; Sheikh et al., 2016; Stamford and Azapagic, 2012). Based on the data availability, a total number of fatalities per unit of utility provided is considered for the electricity and water supply (Table 5). For the cooking heat, only qualitative safety ratings have been available, obtained through stakeholder interviews (Putti et al., 2015). They are expressed as a safety score.
on a scale from 1 to 4, with the former representing the least safe and the latter the safest option.

Total number of fatalities related to electricity generation is estimated based on the supply mix as follows:

$$\text{FE}_{\text{E}} = \sum_{\text{t} \in \text{S}} \text{FR}_{\text{t}} \times \text{EG}_{\text{E},\text{S}}$$  \hspace{1cm} (3)

where:

- $\text{FE}_{\text{E}}$: total number of fatalities related to electricity generation in the current situation or scenario $s$ (no./year)
- $\text{FR}_{\text{t}}$: fatality rate for technology $t$ (no./TWh or no./$1000$ worker-year)
- $\text{EG}_{\text{E},\text{S}}$: annual electricity generation by technology $t$ in the current situation or scenario $s$ (TWh/year).

Applying a similar approach to the estimation of fatalities for water supply yields:

$$\text{FW}_{\text{W}} = \sum_{\text{t} \in \text{S}} \text{FR}_{\text{t}} \times \text{DE}_{\text{W},\text{S}}$$  \hspace{1cm} (4)

where:

- $\text{FW}_{\text{W}}$: total number of fatalities related to water in the current situation or scenario $s$ (no./year)
- $\text{DE}_{\text{W},\text{S}}$: direct employment for water technology/source $t$ in the current situation or scenario $s$ (jobs).
For the cooking heat, a weighted average score is determined based on the safety ratings and the fuel mix as below:

\[ SC_s = \frac{\sum_{f \in S} SR_f \times P_{f,s}}{4} \]  

(5)

where:

- \( SC_s \) overall safety of the cooking fuel mix in the current situation or scenario \( s \) (-)
- \( SR_f \) safety score of cooking fuel \( f \) (-)
- \( P_{f,s} \) fraction of fuel \( f \) in the cooking fuel mix in the current situation or scenario \( s \) (-)
- 4 scaling factor to normalise the range to a scale 0–1.

2.2.4. Security of supply

Security of energy and water supply is an issue that is important for remote communities with limited resources (Dickson et al., 2016; Raghoo et al., 2018). Multiple dimensions of energy and water security are used in research and policy, including environmental quality and price fluctuations (Dickson et al., 2016; Raghoo et al., 2018). As environmental and economic impacts are already considered in other categories, this issue is evaluated here using diversity of supply as an indicator. Diversity is a prominently utilised factor in energy security policies and can be defined as a balanced reliance on a variety of supply options (Stirling, 2010). In this study, the Shannon equitability index (NIST, 2016) has been selected as the diversity indicator:

\[ H_{u,s} = -\frac{1}{\ln U} \sum_{t \in U,S} P_{t,s} \ln P_{t,s} \]  

(6)

where:

- \( H_{u,s} \) Shannon equitability index of utility \( u \) (electricity, cooking heat or water) in the current situation or scenario \( s \) (-)
- \( U \) total number of supply options for utility \( u \) (no.)
- \( P_{t,s} \) fraction of supply from technology/source \( t \) in the current situation or scenario \( s \) (-)

The values for the Shannon equitability index range from 0 (dependent on one source only) to 1 (evenly distributed among multiple sources). Hence, higher values are desired for increasing the security of supply.

2.2.5. Use of local resources

Policies in rural developing areas may incentivise the use of local resources to lower costs and attract investment (Rahman et al., 2013). Residents who prioritise local autonomy can also benefit from the reduced dependence on imported energy and water (Engelen et al., 2016; McKenna et al., 2018). Local resource utilisation can also be defined as supply independence, or the fraction of energy or water that is not imported from outside the remote community:

\[ SI_{u,s} = \sum_{t \in U,S} P_{t,s} \times 100\% \]  

(7)

where:

- \( SI_{u,s} \) supply independence of utility \( u \) in the current situation or scenario \( s \) (%)
- \( U \) set of local technology and resource options.

For electricity generation, solar PV, wind and biomass are considered local resources. All cooking fuels, except for LPG and kerosene, are also sourced locally. In water supply, bottled water is sourced externally.

2.2.6. Social acceptability

Meeting stakeholder requirements for acceptability is long recognised as a crucial barrier for the deployment of renewable energy and water, especially at the community scale (Koirala et al., 2016; Liner et al., 2012; von Wirth et al., 2018; Yaqoot et al., 2016). While user input (e.g. surveys and interviews) is the most direct way of measuring social acceptance, several driving factors have been proposed that can be used as alternative measures. Awareness of benefits (e.g. increased income or improved lifestyle) and coherence with norms and value systems are reported to be key components of social acceptance (Sardianou and Genoudi, 2013; Yaqoot et al., 2016).

For this study, three indicators are proposed as measures of social acceptability of electricity, cooking heat and water supply options, respectively: human development index, use of clean cooking fuels and consumer preference for bottled water.

Availability of electricity can be linked to improved conditions of living, which in turn can be quantified through the human development index (Rojas-Zerpa, 2012):

\[ \text{HDI}_u = 0.0978 \ln \left( \frac{E_u + \min(0.2E_{xs,s}, 0.5E_s)}{4N_{bh,s}} \right) - 0.0319 \]  

(8)

where:

- \( \text{HDI}_u \) human development index in the current situation or scenario \( s \) (-)
- \( E_u \) electricity consumption in the current situation or scenario \( s \) (kWh/year)
- \( E_{xs,s} \) excess electricity generated in the current situation or scenario \( s \) (kWh/year)
- \( N_{bh,s} \) number of households (with four persons) in the current situation or scenario \( s \) (no.).

The excess electricity generated is potentially available for the development of new businesses and public services, contributing further to the development of the community (Dufo-Lopez et al., 2016). For this study, it is assumed that 20% of surplus electricity is available and that any new load cannot exceed 50% of the current load (Rojas-Zerpa and Yusta, 2015).

The use of clean cooking fuels (i.e. LPG, biogas and electricity) leads to household benefits, such as reduced indoor pollution and time for fuel collection, as well as improved gender equity (Putti et al., 2015). Hence, the fraction of clean cooking in a cooking fuel mix is used as an indicator of social acceptability and is estimated as:

\[ \text{CF}_u = \sum_{cfs \in S} P_{cfs,s} \times 100\% \]  

(9)

where:

- \( \text{CF}_u \) total percentage of clean cooking fuels in the current situation or scenario \( s \) (%)
- \( P_{cfs,s} \) fraction of clean cooking fuel \( c_f \) in the current situation or scenario \( s \) (-).

The third social acceptability indicator considered here is the consumer preference for bottled water over other sources. This is reported even in communities with access to tap water and independent of household income (Francisco, 2014; Vásquez, 2017). It is estimated as:

\[ \text{BW}_u = \sum_{bwcs \in S} P_{bwcs} \times 100\% \]  

(10)

where:

- \( \text{BW}_u \) total percentage of bottled water in the current situation or scenario \( s \) (%)
- \( P_{bwcs} \) fraction of water in 18.9 L or 1.5 L bottles in the current situation or scenario \( s \) (-).
Table 6
Indicator weights in the environmental domain

| Environmental issue                  | Indicator | Equal weighting | Environmental Footprint weighting (adapted from (Sala et al., 2018)) |
|-------------------------------------|-----------|-----------------|-------------------------------------------------------------------|
| Agricultural land occupation        | ALOP      | 6.25%           | 2.91%                                                             |
| Global warming                      | GWP       | 6.25%           | 23.14%                                                            |
| Fossil depletion                    | FDP       | 6.25%           | 9.14%                                                             |
| Freshwater ecotoxicity              | FETP      | 6.25%           | 0.70%                                                             |
| Freshwater eutrophication           | FEP       | 6.25%           | 7.15%                                                             |
| Marine ecotoxicity                  | METP      | 6.25%           | 0.70%                                                             |
| Marine eutrophication               | MEP       | 6.25%           | 3.25%                                                             |
| Metal depletion                     | MDP       | 6.25%           | 8.29%                                                             |
| Natural land transformation         | NLTP      | 6.25%           | 2.91%                                                             |
| Ozone depletion                     | ODP       | 6.25%           | 6.93%                                                             |
| Particulate matter formation        | PMFP      | 6.25%           | 0.84%                                                             |
| Photochemical oxidant formation     | POFP      | 6.25%           | 5.25%                                                             |
| Terrestrial acidification           | TAP       | 6.25%           | 6.81%                                                             |
| Terrestrial ecotoxicity             | TETP      | 6.25%           | 0.70%                                                             |
| Urban land occupation               | ULOP      | 6.25%           | 2.91%                                                             |
| Water depletion                     | WDP       | 6.25%           | 9.35%                                                             |

* Estimated according to the ReCiPe method. The “P” in the acronyms stands for “potential.”

2.3. Environmental and economic sustainability assessment

As mentioned earlier, both the environmental and economic sustainability assessments are based on a life cycle approach. The environmental indicators have been estimated through LCA, following the ReCiPe v1.08 method (Goedkoop et al., 2013). All 16 categories included in this version of ReCiPe have been considered (Table 6). An overview of the input data used can be found in Table S3 in the SI.

The LCA modelling has been carried out in GaBi ts 7.3 (Thinkstep, 2016), with the background data sourced from ecoinvent 3.1 (Wernet et al., 2016).

The life cycle costs have been determined following the method proposed by Swarr et al. (2011). They are estimated as the sum of annualised capital costs (ACC) and operating and maintenance costs (OMC), which are in turn equal to:

\[ \text{ACC}_s = \sum_{t \in S} \frac{\text{CC}_t}{\text{Nh}_s} \times \frac{r(1 + r)^h}{(1 + r)^h - 1} \]  
\[ \text{OMC}_s = \sum_{t \in S} \frac{\text{FC}_t + \text{VC}_t + \text{FC}_t}{\text{Nh}_s} + \text{CB}_s \]

where:
- \( \text{ACC}_s \): annualised capital costs per household for the current situation or scenario \( s \) (USD/hh-year)
- \( \text{OMC}_s \): operating and maintenance costs per household for the current situation or scenario \( s \) (USD/hh-year)
- \( \text{CC}_t \): capital costs of technology \( t \) in the current situation or scenario \( s \) (USD)
- \( r \): discount rate (-)
- \( n_t \): lifetime of technology \( t \) (year)
- \( \text{FC}_t \): annual fixed costs of technology \( t \) in the current situation or scenario \( s \) (USD/year)
- \( \text{VC}_t \): annual variable costs of technology \( t \) in the current situation or scenario \( s \) (USD/year)
- \( \text{CB}_s \): annual costs of imported bottled water in the current situation or scenario \( s \) (USD/hh/year).

A discount rate of 10% is used as common for energy systems in developing countries (IRENA, 2018).

The environmental impacts and life cycle costs for the current situation, BAU, Transition and Independent scenarios are reported elsewhere (Aberilla et al., 2020a) and are used here as in input into the MCDA for the integrated sustainability assessment. The impacts and costs of the Advanced and Advanced Independent scenarios have been estimated within the current work. As for the previous scenarios, this has involved designing and optimising the electricity system in HOMER (HOMER Energy LLC, 2017) to determine the optimal ACC and OMC, followed by LCA modelling of each scenario to estimate the environmental impacts. The parameters for the electricity system design (Tables S1 and S2 in the SI) and environmental and economic evaluation (Tables S2 and S3 in the SI) are the same as in the other three scenarios. The optimised system architecture for the Advanced scenario consists of the existing diesel generator considered in the current situation with new biomass gasification capacity to meet the additional demand (Table 2). While the two generation technologies can be operated without energy storage, the optimised HOMER model chose a Li-ion battery installation with a total capacity of 126 kWh to reduce generator and turbine operating hours. The power system in the Advanced Independent scenario relies on electricity from solar and biomass resources. The environmental and economic impacts of these scenarios are discussed in Section 3.2.

2.4. Multi-criteria decision analysis

As mentioned in the introduction, MCDA is used widely in sustainability assessments as it enables stakeholders to understand the trade-offs between different alternatives under consideration and select the one that satisfies their decision criteria and preferences (Azapagic et al., 2016; Cinelli et al., 2014). Due to the variety of frameworks and applications of MCDA, it is necessary to select an appropriate method that is consistent with the goal and scope of the study, as well as the structure of the variables used in calculations (Guarini et al., 2018; Watröbski et al., 2018). To this end, the MCDA method for this study has been selected based on its ability to:

- handle both quantitative and qualitative data;
- rank options and differentiate between acceptable and unacceptable options;
- use weights as an input variable (for sensitivity analysis); and
- identify “hotspots” (i.e. best and worst performing criteria) of each option.

Based on the above criteria and the selection frameworks recommended by Watröbski et al. (2018) and Guarini et al. (2018), the VIKOR method (Opricovic and Tzeng, 2007) has been chosen for this study. VIKOR is a ranking/choice method which determines a “compromise set” from a group of alternatives based on weighted non-commensurable criteria (i.e. the best or set of best options are
chosen among the available options). It is also applicable when the preferences of the decision maker are not expressed (or are flexible) at the outset (Opricovic and Tzeng, 2007). The VIKOR algorithm generates three merit functions which form the basis of the results:

- S, representing the total disutility (i.e. total distance from ideal solution);
- R, representing the maximum regret (i.e. worst score); and
- Q, a function of S and R considering the “compromise strategy” and representing the total score (sustainability score, in this case).

For all three functions, the range is from zero to unity. The numerical value can be interpreted as the distance from the best possible (ideal) solution; hence, lower values are deemed more preferable.

The compromise strategy is represented by a numerical weight \( v \) and can be “maximum utility” \( (v > 0.5) \), “consensus” \( (v = 0.5) \), or “veto” \( (v < 0.5) \). A consensus-building strategy is used here to represent equal decision-making power of different stakeholders. The alternative with the lowest value of \( Q \) (sustainability score) is considered the best option and is included in the compromise set of best alternatives. The next best-ranking options may be added to the compromise set based on rules of acceptable advantage and stability (Opricovic and Tzeng, 2007) (Figure 3).

The MCDA decision tree is shown in Fig. 4. In the base case, all social, environmental and economic indicators are assumed to have equal weights. This assumption is tested through a sensitivity analysis within each of the three sustainability domains as well as between them. For the social criteria, equal weighting per issue rather than per indicator has also been applied (Table 7). The weighted indicators are then assumed to contribute equally to the total score for the domain to which they belong. For the environmental domain, the outcomes for the equal weighting of the LCA indicators are compared with the recommended weights in the Environmental Footprint approach (Sala et al., 2018), adapted for the ReCiPe impact categories (Table 6). Finally, as there are only two economic indicators, there is only one degree of freedom in the variation of the weights; the weight of ACC has been varied accordingly.

### Table 7

| Social issue         | Indicator                                                                 | Equal weighting of indicators | Equal weighting of issues |
|----------------------|---------------------------------------------------------------------------|-------------------------------|---------------------------|
| Human health         | Human toxicity potential (LCA)                                            | 6.25%                         | 5.56%                     |
|                      | Ionizing radiation potential (LCA)                                        | 6.25%                         | 5.56%                     |
|                      | Local air pollution (regionalised impact assessment (van Zelm et al., 2016)) | 6.25%                         | 5.56%                     |
| Direct employment    | Direct employment (DE; Eq. 2)                                            | 6.25%                         | 16.67%                    |
| Safety               | Fatalities in electricity supply (Fe; Eq. 3)                             | 6.25%                         | 5.56%                     |
|                      | Safety of cooking fuels (Sc; Eq. 5)                                      | 6.25%                         | 5.56%                     |
|                      | Fatalities in water supply (Fw; Eq. 4)                                   | 6.25%                         | 5.56%                     |
| Security of supply   | Electricity supply diversity (H1; Eq. 6)                                 | 6.25%                         | 5.56%                     |
|                      | Cooking fuels supply diversity (H2; Eq. 6)                              | 6.25%                         | 5.56%                     |
|                      | Water supply (Hw; Eq. 6)                                                 | 6.25%                         | 5.56%                     |
| Independence         | Electricity supply independence (S1; Eq. 7)                              | 6.25%                         | 5.56%                     |
|                      | Cooking fuels supply independence (S2; Eq. 7)                            | 6.25%                         | 5.56%                     |
|                      | Water supply independence (S3; Eq. 7)                                    | 6.25%                         | 5.56%                     |
| Social acceptability | Human development index (HDI; Eq. 8)                                     | 6.25%                         | 5.56%                     |
|                      | Fraction of clean cooking fuels (CF; Eq. 9)                             | 6.25%                         | 5.56%                     |
|                      | Fraction of bottled water in the mix (BW; Eq. 10)                       | 6.25%                         | 5.56%                     |

### 3. Results and discussion

This section presents first the results of the social sustainability assessment, followed by an overview of the environmental and economic impacts in Section 3.2. The outcomes of their integration via MCDA to determine the overall sustainability of the scenarios in comparison to the current situation are discussed in Section 3.4.

#### 3.1. Social sustainability assessment

The results of the social sustainability assessment are summarised in Table 8 for the 16 indicators considered. As can be seen, the picture is quite mixed across the scenarios, with Independent and Advanced Independent being the best options for seven indicators but also the worst options for four and five others, respectively. The current situation is the least sustainable option for five social sustainability indicators but it has the lowest fatalities in the electricity sector. Transition is the only scenario that is not the worst option for any indicator but it is not the best alternative for any category either. The following sub-sections discuss the results for each social issue in more detail.
3.1.1. Human health

The life cycle human toxicity potential (HTP) is the lowest in the Independent scenario (277.5 kg 1,4-DB eq./year), with 86% attributed to the provision of heat for cooking. In the scenarios without bottled water (Independent and Advanced Independent), HTP is lower and dominated by the cooking heat. The latter is mainly due to the trace metals in the ash from solid biomass fuels, including charcoal (Aberilla et al., 2020c). In contrast, the BAU scenario has the highest HTP (1,041.7 kg 1,4-DB eq.), of which 86% is primarily due to bottled water. Water is also the main contributor (>76%) to the HTP in the current situation and Transition and Advanced scenarios. This is related to the production of plastic bottles and detergents for washing reusable water containers (Aberilla, 2020). Electricity is a minor contributor to HTP in all scenarios (<7%).

The Independent scenario has the lowest ionizing radiation potential (−1.4 kg U\(^{235}\)eq./year) and the BAU the highest (172.1 kg U\(^{235}\)eq./year). The Independent and Advanced Independent scenarios have a net-negative impact (−1.4 and −0.5 kg U\(^{235}\)eq./year, respectively), mainly due to the credits for digestate from biogas production, which displaces mineral fertilisers (Aberilla et al., 2019), as well as due to the absence of bottled water. The water supply contributes 67–77% of the total impact in the four other scenarios, again primarily due to bottled water.

The impact from local air pollution (LAP), expressed here in disability-adjusted life years (DALY), is related to emissions of particulates, nitrogen oxides and sulphur dioxide. The Independent and Advanced Independent scenarios have the highest LAP (51.3 and 55.5 DALY/year, respectively). This is almost solely due to solid biomass fuels which cause >94% of the impact. The Advanced scenario, which has a cleaner cooking fuel mix, has the lowest LAP impact (1.4 DALY/year), although cooking fuels are still the primary contributors to the total (94%).

3.1.2. Direct employment

The majority (73–98%) of direct employment in the current situation and future scenarios is found in the water sector, specifically in water bottling and delivery. Hence, the BAU scenario has the highest direct employment (156 jobs) as it has the greatest fraction of bottled water in the supply mix. By the same logic, the Independent and Advanced Independent provide the lowest direct employment (24 and 28 jobs, respectively) due to the absence of bottled water.

Collection of fuel wood and charcoal is the most significant source of direct employment in the cooking heat system. Interestingly, the current cooking fuel mix has the greatest number of direct jobs compared to the future scenarios. The decline in jobs in
the latter is caused by the prevalence of backyard installations for the production of biogas: these installations are too small in scale and labour requirements to create additional direct jobs. The Advanced scenario, which assumes a full adoption of clean fuels, has the lowest employment related to the cooking fuel supply.

The small-scale electricity systems require at most two full-time employees. However, this may be a significant underestimation as primary data are only available for industrial-scale deployment in developed countries, with employment assumed to be directly proportional to the scale (Rutovitz et al., 2015). Nonetheless, initial estimates suggest that employment in the electricity sector can be up to 21 times higher in scenarios with a greater share of renewables (Advanced and Advanced Independent) than in those that rely on diesel (current situation and BAU). This is further supported by a finding that employment creation in the non-hydro renewables sector in developing countries is 30 times higher than in the fossil fuels sector (Montt et al., 2018). It is noted, however, that at the community-level direct employment for electricity generation is dwarfed by the number of jobs in water supply.

3.1.3. Safety

In the electricity sector, the current situation has the lowest fatality rate (1.8 × 10⁻⁶/year) while the Advanced Independent scenario has the highest (84.2 × 10⁻⁶/year). The latter means that, for an average installation lifetime of 30 years, one in every 396 sites will experience a fatality. The incident rate tends to increase with greater proportion of renewables in the generation mix. This can be related to the higher frequency of accidents per kWh of solar PV and wind compared to diesel generators (Sovacool et al., 2015).

There is a smaller variance in the safety rating of the cooking fuels across the scenarios. Those with higher proportions of fuel wood and crop residues (current situation, Independent and Advanced Independent) are deemed less safe, with ratings of 0.48–0.51 (Table 8). By contrast, the Advanced option, which has a clean fuel mix, is considered the safest with a rating of 0.58. Therefore, these findings suggest that the adoption of clean cooking fuels would improve household safety. However, it should be noted that safety considerations in the rest of the life cycle of the fuels are excluded due to a lack of data.

Since the water supply is the major contributor to direct employment in all scenarios, the rankings in this criterion are also reflected in the safety aspect. The BAU scenario, with the highest employment in the water supply, has 16 times more fatalities (once every 174 years) than the Independent and Advanced Independent scenarios which provide the fewest water-related jobs (once every 2,857 and 2,381 years, respectively).

### 3.1.4. Security of supply

Security of electricity supply, as measured by the Shannon equitability index, is the lowest for the current situation and BAU (0) due to the reliance on diesel for electricity generation. The Advanced scenario also has a low electricity diversity score (0.04) as there is a high dependence on biomass. In contrast, the Transition and Independent scenarios have the highest scores (0.51 and 0.49) since they utilise more diverse power sources.

The diversity index is relatively high for cooking fuels in most scenarios (0.69–0.8). The exception is the Advanced scenario (0.36) which only includes three of the seven potential cooking fuels, while the other scenarios utilise five or more types (Table 1). The BAU and Transition scenarios include all seven fuels, but these are distributed more evenly in the Transition scenario, which has the highest diversity score (0.8).

As all scenarios utilise four or five water sources, the diversity index ranges from 0.58 (current situation) to 0.78 (Advanced). Comparing the current water supply to that of the BAU scenario, the increase in the Shannon index is attributed to the higher share
of bottled water, resulting in a more even spread of supply. It is also notable that the absence of bottled water in the Independent and Advanced Independent scenarios decreases their diversity scores relative to the Transition and Advanced scenarios (0.61 and 0.63 vs 0.74 and 0.78, respectively).

3.1.5. Independence

Since the Independent and Advanced Independent scenarios have no imported electricity, cooking fuels and water, these scenarios have full supply independence in all three sectors. The Transition and Advanced are also almost independent (99%) but they still use some diesel as a backup for biomass power. By contrast, the independence score for electricity in the current situation and BAU is 0% as they are fully dependent on diesel for electricity generation.

The supply independence of the current cooking fuel mix is relatively high (56%). This decreases in the BAU and Advanced scenarios (47% and 31%, respectively) as more LPG is present in their cooking fuel mix. The introduction of biogas in the Transition scenario increases the independence of cooking to 67%.

High utilisation of local freshwater resources in all scenarios results in the independence of water supply of at least 77% (BAU). The Independent and Advanced Independent options are fully independent as imported bottled water is not used.

3.1.6. Social acceptability

All scenarios have an HDI below the “low human development” threshold of 0.504 (UNDP, 2018), although the Advanced and Advanced Independent scenarios come close (0.48 and 0.5, respectively). To reach the HDI of small-island development states (0.676 (UNDP, 2018)), total electricity generation, including that for water production, would need to be at least 72 times higher than at present. However, these findings should be interpreted with care as the correlation of HDI to electricity production is based on national values, which include demand from commercial and industrial sectors (Rojas-Zerpa, 2012).

The share of clean fuels is the highest in the Advanced (100%) scenario while the Independent and Advanced Independent have lower fractions (29% and 31%, respectively) than in the current situation since the absence of LPG in the fuel supply is compensated by higher use of solid biomass.

Finally, the Independent and Advanced Independent scenarios have the lowest score related to bottled water (0%) and the BAU the highest (23%). This means that, based on consumer preferences for bottled water, the first two are the least and the BAU is the most socially-acceptable scenarios.

3.2. Environmental sustainability assessment

The life cycle environmental impacts for the current situation and future scenarios are summarised in Table 9. As can be seen, BAU has the highest impacts in 12 of the 16 categories. In contrast, the Independent and Advanced Independent have the lowest values, also for 12 impacts. Similar to the social sustainability, the Transition scenario is the only option that is not the worst in any indicator but it is not the best in any either. As the results for the BAU, Transition and Independent scenarios have previously been presented elsewhere (Aberilla et al., 2020a), the discussion below focuses on the scenarios developed as part of the current work.

With almost all of the electricity in the Advanced scenario derived from waste biomass gasification (Table 1), the impacts of electricity consumption per household are >97% lower than for the current situation. The exceptions are terrestrial and human

| Impact per household-yeara | Current situationb | Business as usualb | Transitionb | Independentb | Advancedc | Advanced Independentc |
|----------------------------|-------------------|--------------------|-------------|--------------|-----------|-----------------------|
| ALOP (m³/a)                | 54.6              | 88.3               | 36.7        | 0.3          | 130.4     | 0.6                   |
| GWP (kg CO₂ eq.)           | 1712.7            | 2309.3             | 1279.9      | 513.8        | 1782.6    | 523.3                 |
| FDP (kg oil eq.)           | 522.5             | 766.7              | 316.8       | -7.4         | 550.8     | -5.5                  |
| FETP (kg 1,4-DB eq.)       | 64.6              | 105.3              | 44.4        | 0.9          | 70.3      | 2.2                   |
| FEP (g P eq.)              | -692.7            | -1389.5            | -3509.8     | -3391.9      | -3701.9   | -3531.7               |
| METP (kg 1,4-DB eq.)       | 53.7              | 87.3               | 36.9        | 0.9          | 57.4      | 2.0                   |
| MEP (g N eq.)              | 1188.5            | 62.3               | -2814.6     | -3366.8      | -2103.5   | -3507.3               |
| MDP (kg Fe eq.)            | 65.4              | 99.4               | 51.9        | 17.7         | 77.1      | 21.2                  |
| NLTP (cm²)                 | 2191.7            | 2833.3             | 1191.6      | -72.4        | 2917.5    | -61.4                 |
| ODP (mg CFC-11 eq.)        | 206.0             | 290.4              | 124.0       | -2.8         | 193.3     | -1.3                  |
| PMFP (kg PM₁₀ eq.)         | 12.8              | 7.8                | 8.8         | 9.8          | 2.4       | 13.2                  |
| POFP (kg NMVOC)            | 44.3              | 25.4               | 28.3        | 34.7         | 6.9       | 37.6                  |
| TAP (kg SO₂ eq.)           | 8.4               | 10.4               | 2.1         | -1.3         | 5.2       | -1.8                  |
| TETP (g 1,4-DB eq.)        | 434.2             | 442.8              | 476.3       | 455.3        | 991.2     | 530.0                 |
| ULOP (m³/a)                | 9.4               | 13.0               | 2.1         | -3.5         | 8.8       | -2.4                  |
| WDP (m³)                   | 2229.1            | 3579.6             | 1641.6      | 236.6        | 2448.9    | 285.4                 |

aFor acronyms, see nomenclature.
bPreviously reported in Aberilla et al. (2020a).
cEstimated as part of this work.
toxicity which are eight and two times higher, respectively, primarily derived from the management of residual ash from cooking fuels (Aberilla et al., 2019). The use of biogas for cooking brings credits for eutrophication, among other categories, while transition away from solid biomass fuels reduces air pollution significantly (Aberilla et al., 2020c). However, greater adoption of LPG implies a 22–26% increase in fossil depletion, ozone depletion and land transformation. Owing to the higher water consumption, the water sector sees an average increase across the impacts of 61%. This in turn increases the total impacts in nine categories by 3–139% above the current situation, including a 4% higher total global warming potential per household. However, net reductions relative to the current situation are seen in the remaining seven impacts as credits in the cleaner cooking fuel mix counteracts the higher impacts from the water supply mix.

The Advanced Independent scenario shows similar trends as the Independent scenario since both maximise the use of local resources. However, due to the greater consumption of energy and water in the former, its impacts are 2–146% higher per household than in Independent. The exceptions to this trend are eutrophication and acidification, for which the Advanced Independent scenario has 4–41% lower impacts. This is due to a lower share of charcoal in the cooking fuel mix which offsets the impact increase in the electricity and water parts of the synergism system.

3.3. Economic sustainability assessment

The estimated capital, operating and total life cycle costs are summarised in Table 10; for the levelised costs, see Table S4 in the SI. As for the environmental sustainability assessment, the costs of the current situation and the BAU, Transition and Independent scenarios have been discussed in previous work (Aberilla et al., 2020a) so that the discussion below considers the Advanced and Advanced Independent scenarios in comparison with the other scenarios. They both have lower total life cycle costs than the current situation (2,448 and 291 USD/hh-year, respectively) due to lower unit costs in all three utility sectors, despite the increased household consumption. Similar to the other future scenarios, the ACC of these scenarios are higher than at present, with increased investment required for the cooking fuels (almost five times higher) and water (36–47% higher) supply due to additional stoves and water production capacity (mainly desalination). However, the OMC sees a reduction of 18–98% for each utility, with the greatest decrease in the water supply mix of the Advanced Independent scenario due to the absence of bottled water. The lower cost of electricity also helps to reduce the cost of water, especially in these two scenarios where desalination contributes 34–42% of the water supply.

However, the Advanced Independent scenario has the highest ACC (165 USD/hh-year), 54% above the current cost (107 USD/hh-year). The infrastructure for water supply accounts for 63–79% of capital costs in all scenarios, with a trend increasing with desalination capacity. The future cooking fuel scenarios have higher capital requirements than at present, in part due to the additional stove requirements, as well as the construction of backyard anaerobic digesters. Scenarios with renewable energy have lower capital costs per unit of energy delivered than those relying only on diesel generators (current situation and BAU). Although per-installation capital costs for renewable energy generation are higher than for diesel generators, the longer lifetime electricity production results in lower annualised capital costs.

Table 10
Economic costs for the current situation and future scenarios.

| Costs (USD/hh-year) | Current situation | Business as usual | Transition | Independent | Advanced | Advanced Independent |
|---------------------|------------------|------------------|------------|-------------|----------|-----------------------|
| Annualised capital costs |                  |                  |            |             |          |                       |
| Electricity         | 16.55            | 25.31            | 6.16       | 5.99        | 5.78     | 12.84                 |
| Cooking             | 5.94             | 18.32            | 23.16      | 28.29       | 29.28    | 28.37                 |
| Water               | 84.24            | 73.78            | 85.69      | 94.74       | 114.45   | 123.51                |
| Total               | 106.73           | 117.41           | 115.02     | 129.03      | 149.52   | 164.72                |
| Operating and maintenance costs |              |                  |            |             |          |                       |
| Electricity         | 29.73            | 76.63            | 5.16       | 4.30        | 10.66    | 9.94                  |
| Cooking             | 103.46           | 93.03            | 73.45      | 61.26       | 72.40    | 57.01                 |
| Water (total)       | 2704.29          | 5077.32          | 2198.92    | 36.88       | 2215.10  | 59.09                 |
| Water (bottled) g   | 2677.46          | 5031.73          | 2172.44    | -           | 2173.45  | -                     |
| Total               | 2837.48          | 5246.98          | 2277.54    | 102.43      | 2298.16  | 126.04                |
| Total life cycle costs |                |                  |            |             |          |                       |
| Electricity         | 46.28            | 101.93           | 11.33      | 10.29       | 16.44    | 22.79                 |
| Cooking             | 109.40           | 111.36           | 96.61      | 89.55       | 101.67   | 85.38                 |
| Water               | 2788.53          | 5151.10          | 2284.61    | 131.62      | 2329.56  | 182.60                |
| Total               | 2944.21          | 5364.39          | 2392.56    | 231.46      | 2447.67  | 290.76                |

aPreviously reported in Aberilla et al. (2020a).
bEstimated as part of this work.
cPurchase costs.
The BAU scenario has the highest operating costs (5247 USD/ton-year) and the independent the lowest (102 USD/ton-year). These are largely related to the costs of bottled water (Table 10), except in the scenarios without it (Independent and Advanced Independent). Excluding the cost of bottled water, the remaining operating costs of water supply is the lowest in the current situation and the highest in the Advanced Independent scenario. The latter is due to desalination which is energy intensive and hence costly. The BAU scenario has the greatest power of cost generation, with costs of fuel being the primary contributor. The costs of cooking heat are the highest for the current situation due to poorer stove efficiencies compared to the future scenarios.

3.4. Sustainability of the current situation and future scenarios

This section integrates the above results through MCDA to determine the overall sustainability of the scenarios. Prior to that, the overall social, environmental and economic sustainability, also evaluated via MCDA, is discussed first.

3.4.1. Social sustainability

Assuming equal weighting of all the 16 indicators, the Transition scenario emerges as the best option (total score Q = 0.53), while the current situation is the worst (Q = 1.0), followed closely by BAU (Q = 0.99); see Fig. 5. However, changing from the indicator to issue weighting affects the outcomes. Although the Transition scenario remains the best option (Q = 0.18), the rankings of the other scenarios shift almost completely (Fig. 5). The Advanced and Independent scenarios are now ranked bottom (Q = 0.65 and 0.69) and comparable to the current situation (Q = 0.68), while BAU is the second best option (Q = 0.33). The reasons for this sensitivity to the weighting approach are revealed in Table 11 which details the contribution of the disutility scores (distance from the ideal solution) for each social sustainability issue. It can be inferred that the Transition scenario, although the most socially sustainable option, derives most of its disutility from social acceptability. This is also the case for the Independent and Advanced Independent scenarios. The Advanced option has a high disutility in safety and security of supply, and BAU in human health and independence.

The weighting for direct employment as an indicator is notably higher in the weighting of issues than the individual indicators (Table 7). This in turn leads to the increased contribution of employment to the Q value of the Independent and Advanced Independent scenarios when applying the per-issue instead of indicator weighting (36% versus 16% for Independent and 33% versus 14% for Advanced Independent). This suggests that the difference in total employment levels between the scenarios can be a significant factor in the social sustainability rankings. This also warrants further investigation into the assumption that jobs in the electricity, cooking fuels and water supply chains are equally desirable to the stakeholders.

3.4.2. Environmental sustainability

Aggregating the impacts using the equal and Environmental Footprint (EF) weighting in turn yields the overall scores presented in Fig. 6. For the equal weights, the Transition scenario is the most environmentally sustainable (Q = 0.18), followed closely by the Independent (Q = 0.19). However, under the EF weighting regime, the Independent scenario is the best possible option (Q = 0). These differing outcomes highlight a trade-off between climate change and air pollution: at equal weights, the Independent scenario has a 7% higher sustainability score than the Transition scenario, with 44% of the disutility derived from smog formation potential (POPF). On the other hand, the EF weighting places greater importance on climate change than air pollution, resulting in a preference for the Independent and Advanced Independent options.

Since the BAU scenario has the highest impacts in most categories, it is the worst option for both weighting schemes. The disutility in BAU (Table 12) is relatively evenly distributed across the impacts for equal weighting. However, for the EF weighting scheme, global warming and resource depletion have the highest disutilities, largely attributed to diesel generators and plastic bottles. The current situation is the second worst option in both cases (Q = 0.92 for equal and Q = 0.69 for EF weighting), with eutrophication and particulate matter formation (PMFP) being the disutility hotspots under both the weighting schemes.

While the Independent and Advanced Independent scenarios are the best options in almost all the categories, they have high PMFP and POPF due to the solid biomass cooking fuels. Consequently, the Independent and Advanced Independent scenarios have the lowest total disutilities for both weighting schemes.

3.4.3. Economic sustainability

For equal weights (0.5) of the ACC and OMC, the most economically sustainable options are the Independent and Transition scenarios. However, this outcome is highly sensitive to the relative weights, as illustrated in Fig. 7. The sensitivity analysis shows that the Independent scenario is acceptable (included in the VIKOR compromise set) for ACC weights not exceeding 0.70; it is also the only acceptable option for the weights in the range of 0.25 to 0.45.

![Fig. 5. Social sustainability scores for the current situation and future scenarios](image-url)
Table 11
Contribution of the disutility function to the total scores under different weighting regimes for social sustainability issues and indicators

| Issue                  | Current situation | BAU | Transition | Independent | Advanced | Advanced Independent |
|------------------------|-------------------|-----|------------|-------------|----------|-----------------------|
|                        |                   |     |            |             |          |                       |
| **Equal weighting of indicators** |                   |     |            |             |          |                       |
| Human health           | 21%               | 25% | 24%        | 15%         | 17%      | 16%                   |
| Direct employment      | 6%                | 0%  | 9%         | 16%         | 7%       | 14%                   |
| Safety                 | 4%                | 16% | 20%        | 13%         | 28%      | 21%                   |
| Security of supply     | 23%               | 18% | 3%         | 19%         | 23%      | 20%                   |
| Independence           | 22%               | 29% | 15%        | 0%          | 16%      | 0%                    |
| Social acceptability   | 24%               | 13% | 29%        | 38%         | 9%       | 29%                   |
| **Equal weighting of issues** |                   |     |            |             |          |                       |
| Human health           | 18%               | 25% | 20%        | 11%         | 15%      | 12%                   |
| Direct employment      | 16%               | 0%  | 24%        | 36%         | 18%      | 33%                   |
| Safety                 | 4%                | 16% | 17%        | 10%         | 24%      | 16%                   |
| Security of supply     | 20%               | 18% | 3%         | 14%         | 21%      | 16%                   |
| Independence           | 20%               | 29% | 13%        | 0%          | 14%      | 0%                    |
| Social acceptability   | 21%               | 13% | 24%        | 29%         | 8%       | 23%                   |

*No shading indicates the lowest and the red shading the highest contribution.*
In contrast, the Transition scenario is part of the compromise set in the upper range of ACC weights. Greater emphasis on capital costs also leads to a preference for the current situation. The Advanced Independent and BAU scenarios only become economically acceptable options at the low and high extremes of capital-cost weights, respectively (Fig. 7).

3.4.4. Overall sustainability

Provided the weights of the social, environmental and economic domains remain equal, the use of different weighting schemes for the individual social and environmental indicators does not affect the overall outcome of the MCDA (Fig. 8). The compromise set of the most sustainable options includes the Independent and Tran-
Table 12
Contribution of the disutility function to the total scores under different weighting regimes for environmental impacts.

| Impact | Current situation | Business as usual | Transition | Independent | Advanced | Advanced Independent |
|--------|-------------------|-------------------|------------|-------------|----------|----------------------|
|        | Equal weighting   |                   |            |             |          |                      |
| ALOP   | 4%                | 5%                | 5%         | 0%          | 11%      | 0%                   |
| GWP    | 6%                | 8%                | 7%         | 0%          | 7%       | 0%                   |
| FDP    | 6%                | 8%                | 7%         | 0%          | 8%       | 0%                   |
| FETP   | 5%                | 8%                | 7%         | 0%          | 7%       | 1%                   |
| FEP    | 9%                | 4%                | 1%         | 4%          | 0%       | 2%                   |
| METP   | 5%                | 8%                | 7%         | 0%          | 7%       | 1%                   |
| MEP    | 9%                | 6%                | 3%         | 2%          | 3%       | 0%                   |
| MDP    | 5%                | 8%                | 7%         | 0%          | 8%       | 2%                   |
| NLTP   | 7%                | 8%                | 7%         | 0%          | 11%      | 0%                   |
| ODP    | 6%                | 8%                | 8%         | 0%          | 7%       | 0%                   |
| PMFP   | 9%                | 4%                | 10%        | 42%         | 0%       | 45%                  |
| POFP   | 9%                | 4%                | 10%        | 46%         | 0%       | 37%                  |
| TAP    | 7%                | 8%                | 5%         | 3%          | 6%       | 0%                   |
| TETP   | 0%                | 0%                | 1%         | 2%          | 11%      | 8%                   |
| ULOP   | 7%                | 8%                | 6%         | 0%          | 8%       | 3%                   |
| WDP    | 5%                | 8%                | 7%         | 0%          | 7%       | 1%                   |
|        | Environmental footprint weighting |                   |            |             |          |                      |
| ALOP   | 2%                | 2%                | 2%         | 0%          | 5%       | 0%                   |
| GWP    | 21%               | 27%               | 25%        | 0%          | 30%      | 1%                   |
| FDP    | 8%                | 11%               | 10%        | 0%          | 12%      | 0%                   |
| FETP   | 1%                | 1%                | 1%         | 0%          | 1%       | 0%                   |
| FEP    | 10%               | 4%                | 1%         | 4%          | 0%       | 2%                   |
| METP   | 1%                | 1%                | 1%         | 0%          | 1%       | 0%                   |
| MEP    | 4%                | 3%                | 1%         | 1%          | 2%       | 0%                   |
| MDP    | 7%                | 10%               | 9%         | 0%          | 11%      | 2%                   |
| NLTP   | 3%                | 3%                | 3%         | 0%          | 5%       | 0%                   |
| ODP    | 7%                | 8%                | 8%         | 0%          | 9%       | 0%                   |
| PMFP   | 13%               | 6%                | 15%        | 58%         | 0%       | 64%                  |
| POFP   | 7%                | 3%                | 8%         | 34%         | 0%       | 28%                  |
| TAP    | 8%                | 8%                | 5%         | 2%          | 7%       | 0%                   |
| TETP   | 0%                | 0%                | 0%         | 0%          | 1%       | 1%                   |
| ULOP   | 3%                | 3%                | 2%         | 0%          | 4%       | 1%                   |
| WDP    | 7%                | 11%               | 10%        | 0%          | 11%      | 1%                   |

* No shading indicates the lowest and the red shading the highest contribution.
* For the abbreviations, see the nomenclature.

sition scenarios, with the former having the best overall sustainability score (Q = 0) in all the combinations of weightings. On the other hand, the BAU scenario is the worst option (Q = 1).

Across the range of top-level domain weights, there is generally a good agreement on the rankings resulting from different environmental and social weighting schemes. Therefore, for brevity, the remaining discussion focuses on the results using the Environmental Footprint weighting scheme for environmental indicators and equal weighting of social sustainability issues (“EE, PT”).

Contribution analysis of disutility function at equal weights between the three domains (Fig. 10) shows that the Independent and Transition scenarios rank in the better half across all domains, with the former ranking best in economic impacts and the latter in social aspects. The opposite is true for the BAU scenario which is worst in environmental impacts and second worst in the other domains. For the remaining three scenarios, their relative rankings suggest trade-offs in their performance across the three areas of evaluation. The Advanced Independent scenario, despite being the
The best option for environmental impacts, has an overall ranking that is only better than the BAU scenario. The high capital costs contribute significant disutility (S-score) and regret (R-score), resulting in a comparatively worse Q-score. The Advanced scenario has worse rankings in the environmental and economic domains than the Advanced Independent scenario but has lower total disutility and higher ranking than the latter. While capital cost is also the hotspot in the former, it has a lower impact (and consequently better R-score) than the latter. The current situation has poor performance in the social and environmental domains, but its relative advantage in the economic aspects (notably by having the lowest capital costs) leads to an overall sustainability score that it better than for the Advanced and Advanced Independent scenarios. These observations highlight that, although there are technologies that are environmentally and socially acceptable, innovative business and financing models are needed to accelerate sustainable development in remote communities.

The top-level domain weights have been varied in a sensitivity analysis and the resulting compromise sets are presented as a ternary diagram with seven regions (Fig. 9). Region A is at a high social and low environmental weight where the BAU scenario can be considered a sustainable option, together with the Transition and Advanced scenarios. The last two sit in Region B – increasing the environmental weight to up to 0.3 within this region makes them both still viable.

The Advanced Independent scenario is found to be an acceptable option when the weight of the economic indicators is low (regions C and D). In contrast, the Transition scenario is no longer a member of the compromise set at low economic and high environmental weights (Regions D and G). The Independent scenario is a sustainable option when the social domain does not dominate (Regions D, F and G). Interestingly, there is a set of domain weights whereby only the Transition or Independent scenario is acceptable (Regions E and G, respectively). These two scenarios also span the greatest area in the weighting space, highlighting the robustness of the finding that these scenarios are the most sustainable options.

To analyse further how the rankings change for different preferences, more extreme weighting regimes are considered in Fig. 10, where one domain is eight times more important than the other two domains. For example, for the case "Environmental x8", the weight of the environmental domain is 0.8 and the economic and social domains are each weighted at 0.1. These extreme weighting regimes can be mapped onto the ternary diagram in Fig. 9 such that, for instance, ‘Environmental x8’ sits on the border between Regions D and G of Fig. 9.

The contribution analysis of the disutility functions at these weights, as well as the total sustainability scores, are shown in Fig. 10. At the equal domain weights, the social disutility has the lowest variation (Q = 0.13 – 0.22) and the environmental disutility the highest (Q = 0.03 – 0.30). This suggests that the trade-offs between the social indicators even out, with the differences in the environmental performance determining the relative sustainability of the scenarios.
The rankings under equal and economic-dominant weights are the same, with the Independent and Transition scenarios identified as the most sustainable options. Placing greater importance on the environmental indicators results in the Advanced Independent and Independent scenarios ranking as the most sustainable alternatives. The Transition scenario is the best option if the social domain is eight times more important than the other two domains, with the Advanced scenario also being an acceptable compromise solution.

4. Conclusions and recommendations

This study has quantified the overall sustainability of synergistic supply of electricity, heat for cooking and water in remote communities. Five 2030 scenarios have been considered and compared to the current situation for a prototypical remote community. The results of the design and optimisation of the synergen systems carried out for different scenarios show that increased demand for energy and water in remote communities can be satisfied through a combination of technologies that are already commercially available.

The social sustainability assessment reveals that at equal weighting of all the 16 indicators considered, the Transition scenario is the best option under both weighting schemes considered (weighting of indicators and of issues). The Independent scenario has the lowest human toxicity and ionizing radiation potentials, but has high impacts from local air pollution and the lowest direct employment. The opposite is true for the BAU scenario which has the highest life cycle human health impacts, but low local emissions, as well as high employment and social acceptability. Security of supply, measured through diversity of sources, is the highest in the Transition scenario, while the Independent and Advanced Independent have the highest independence scores. With respect to safety, the lowest fatality rates in electricity supply are found for the current situation. The Advanced scenario, which has a clean fuel mix, is considered the safest option for cooking heat, while the Independent and Advanced Independent have the lowest fatalities associated with water supply.

Considering the overall social, environmental and economic sustainability and assuming equal weighting of all the three domains, the Independent scenario emerges as the most sustainable option. Conversely, the BAU scenario has the worst overall sustainability score due to high environmental impacts and economic costs. The Independent scenario remains the most sustainable alternative across a broad range of weights, even if the environmental or economic domains are considered to be eight times more important than the social. However, if social impacts are prioritised, the Transition scenario is the most sustainable outcome.

In addition to showing the trade-offs between different sustainability aspects, these results also demonstrate that current off-grid energy and water supply can be transitioned sustainably to self-sufficient systems, enabling remote communities to use indigenous resources and locally-installed technologies. The scenarios developed in this study can be used as a template for remote communities with similar resources and socio-economic conditions. Furthermore, the methods presented here can be applied by local authorities and community developers to enhance development projects by considering a broader range of sustainability issues and multiple possible outcomes.

The synergen approach applied in the development of the scenarios is based on systems thinking in community development to mitigate potential negative impacts through strategic coupling of energy and water systems. Financial viability and social acceptability of energy access programmes can be improved by leveraging synergies between different provisioning systems in a community. For example, if current household consumption of electricity is too low to make an off-grid installation viable, consumption in other sectors, such as irrigation and desalination, can be considered to justify larger and more cost-effective systems.

Future work should include stakeholder consultations to determine their preferences for different sustainability issues and indicators. In practice, planning and decision making should be based on information that best represents the actual community and relevant stakeholders. While no weighting set can be generalised outside a specific decision context, the results presented here demonstrate how outcomes and aspirations articulated by stakeholders in community development can be used for scenario development and identification of sustainable energy and water systems.

The approach presented here could also be applied to other cases, such as identifying sustainable supply chains for the use of natural resources in remote communities. Another interesting direction for future work is the dynamics of the transition from the current situation to the various future scenarios. Multi-year simulation and dynamic life cycle assessment methods would be required for such an analysis.

Declaration of Competing Interest

The authors declare no conflict of interest

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Supplementary materials

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