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Integrated Renewable Energy and Resource Network Optimisation for Off-Grid Energy Supply to Rural Communities

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This study develops an optimal integrated energy network for 15 decentralised rural neighbourhood structures (sectors and clients) that are isolated from the main energy grid in Tsumkwe, Namibia. The structures have different demand profiles dictated by the type of building, the time of day, as well as the season. Because of the logistical difficulty and cost implication associated with bringing fuel (such as diesel) from distant suppliers to remote locations, the isolated communities need to make optimum use of the locally available biomass resources and have effective planning of outsourced fuel in their supply chain (SC). Biomass resources considered in this study are animal dung, fuel wood, human waste, and crop residue. These biomass sources were coupled with photovoltaic (PV) units and lithium storage batteries. The optimal network showed PV-SC selection with minimal battery storage selection. The SC shows a favourable cost advantage over the energy storage batteries and can support most of the intermittency of the PV supply. The SC contributed 94.1 % and 42.7 % with regard to the total cost and energy supply to demand structures. The PV panel was the preferred energy supply technology for the Distributed Energy System (DES) because of its cost effectiveness (57.2 % and 5.94 % energy and cost contribution to the network). The total annual power supply of the minigrid is 0.465 GWh/y. The total annual cost (TAC) of the minigrid was found to be N$ 2,580,000. The minigrid power production cost was found to be 39 % more expensive than energy from the National grid tariff. However, it does not require long-range transmission and makes provision for local job opportunities.

1. Introduction

About 50 % of the Namibian population is unelectrified (30,000 households), consisting of 70 - 80 % of the rural population (Matthys, 2022). Exploration of the potential for biomass as an energy vector is advantageous for the country due to its vast land and low population density of about three persons per km^2. In addition, Namibia is second in the world, with available solar irradiation of 3,000 kWh/m^2 in the southern part of the country (Gesto Energy Consultants, 2012). This unique aspect of the country allows for the usage of available biomass and the installation of solar panels in the largely available land that does not compete with agricultural, industrial, or residential projects.

Several works, such as Alavi et al. (2015), who studied the uncertainty in energy management and van der Heijde (2019), who investigated the design and optimisation of a fictitious solar district heating system with seasonal thermal energy, both analysed isolated grids considering hypothetical scenarios and communities. On the other hand, some studies focused on the technical aspects of isolated rural grids and how they can be monitored. These studies ignored the optimal resource allocation, or sharing approach, that meets the demand for energy considering the intermittency in resource availability and variability in energy demand. Another group of studies, such as Azimoh et al. (2016), focused on the socio-economic aspects of decentralised hybrid grid systems on existing communities without optimisation of the networks. Other studies, such as (Isafiade and Short, 2022), considered both the economic and the environmental impacts of heating and cooling for a hypothetical site. Compared to the above-mentioned studies, the novelty of this work lies in simultaneously optimising the design of the network and the Supply Chain (SC), which contributes to the resources used in the

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designed network. This is an improvement on the work by Mehleri et al. (2012), which presented a Mixed-Integer Linear Programming (MILP) superstructure model for the optimal design of Distributed Energy System (DES) for small neighbourhoods and De Mel et al. (2022) that presented an open-source optimisation model for DES design with optimal power flow. This study incorporates the SC strategy discussed by Mutenure et al. (2018) to address the challenges presented by the varied availability of biomass resources to develop a model that will be used to obtain optimal network configurations for Tsumkwe, Namibia. To the best of the authors' knowledge, the concept of SC networks has not been explicitly included in hybrid DES, as proposed in this study. The additional novelty of this work comes with the application of the developed model to Tsumkwe Namibia.

This paper focuses on a hybrid PV-SC-powered mini-grid for Tsumkwe, a rural community in Namibia, isolated from the main energy grid system. Rural unelectrified areas in Namibia (of which Tsumkwe is a typical example) are characterised by low population densities and a highly dispersed settlement. These communities are not viable for connection to the main national grid system in the foreseeable future, making it imperative to consider mini-grid electrification. With the country's high dependency on power imports of about 70 %, it is important for Namibia to consider other options for electrifying rural communities outside of extending the already strained main National grid.

2. Problem statement

For a given set of renewable and non-renewable energy sources and a set of energy conversion and storage technologies, the goal is to develop an optimal integrated SC and DES for Tsumkwe rural community, considering the hourly and seasonal availability and variability in the energy supply and demand. The integrated energy network superstructure is shown in Figure 1. The energy network developed must be able to meet all the energy requirements for Tsumkwe optimally, irrespective of variations in resource availability and fluctuations in energy demand. This will be done by formulating the model as a MILP with the objective of optimising Total Annual Cost (TAC). The TAC will also be informed by the unit costs to install, maintain, and operate the technologies, including the transportation of the resources and energy produced between supply, technology, and demand locations. A multiple timeframe SC network will be used to model the fluctuations in the energy sources and sinks.

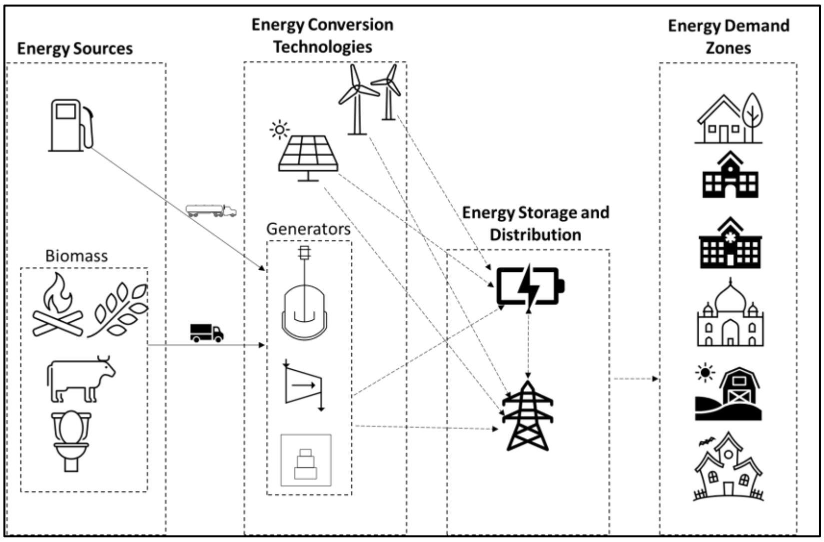

Figure 1: Integrated SC superstructure, adapted from Jegede et al. (2023)

3. Methodology

This study formulates a model that finds the optimal match of the energy supply to demand zones on hourly and seasonal time discretisations. Four seasons are considered, namely winter, autumn, summer, and spring. The TAC objective function of the integrated power SC and DES, which is modelled as a MILP, is represented as shown in Eq(1).

$$TAC = Cost^{CC} + Cost^{OP} + Cost^{SC} \tag{1}$$

Where $Cost^{CC}$, $Cost^{OP}$, $Cost^{SC}$ are the annualised capital cost, annualised operational and maintenance cost, and the annualised SC cost of the integrated system. Details of the cost parameters and variables are explained in Jegede et al. (2023). The MILP model was developed in the Pyomo algebraic modelling environment (Bynum et al., 2012) and solved using the CPLEX solver (IBM, 2022).

For a continuous supply of energy, the SC network aspects to be considered must be informed by operational and system constraints dictated by the generation of energy from both renewable and non-renewable energy sources, and the transmission of energy to consumers based on need, energy storage, and transportation of fuel required to produce electricity to consumers. Details of the constraints are presented in Jegede et al. (2023).

The available Direct Normal Irradiation (DNI) refers to the shortwave solar radiation received by a normal surface to the sun and is a critical parameter for determining the effectiveness and efficiency of tilted and sun-tracking PV modules. The DNI output for Tsumkwe is obtained from the global solar atlas website (Global Solar Atlas, 2023). The average monthly solar DNI in Tsumkwe is generally sufficient between 07:00 and 17:00 every day, providing an average annual DNI of 2,354.2 kWh/m^2.

The SC model of this paper consists of biomass energy sources that are converted to power by three different technologies, namely biodigester, steam turbine, and diesel generator. Each energy source's cost varies for different seasons, while the conversion technology sizes are fixed across the seasons with varying seasonal throughputs that affect operational costs. Energy conversion technology is modelled with fixed efficiencies, and units are sized according to their maximum peak time load demand. Because of the economic consideration of sourcing biomass fuel only from the immediate surroundings of the mini-grid, the available biomass is capped to a maximum of about 100 kg of each resource available per day. These amounts were informed by the available resources as well as the energy content of each resource, as shown in Table 1. Energy content values of the various biomass shown in the table are on a dry basis. Lithium batteries are available to store solar energy when the energy supply exceeds demand. The PV capacity was uncapped to allow for as much dependency on PV technology as possible. The power demand requirements were profiled for the households, industries, and services sectors by using typical demand values and profiles. The key parameters used in the model are shown in Table 1, as reported in Jegede et al. (2023).

Table 1: Key Parameters for case study ***(****Adapted from Jegede et al., 2023)*

Parameter	Value
Capital cost of PV panel	9.540 N$/panel
Variable operational cost of PV panel	0.11 N$/kWh
Fixed operational cost of PV panel	265 N$/(kW.y)
Efficiency of PV panel	0.135
Capital cost of lithium batteries	884 N$/kW
Efficiency of lithium batteries	0.98
Capital cost of diesel generator	1,480 N$/kW
Capital cost of steam turbine	91,800 N$/kW
Capital cost of biodigester	15,600 N$/kW
Cost of diesel	21.08 N$/L
Energy content of diesel	10 kWh/L
Cost of fuel wood	0.941-1.48 N$/kg
Energy content of fuel wood	4.5 kWh/kg
Cost of animal dung	2.12-4.24 N$/kg
Energy content of animal dung	5 kWh/kg
Cost of human waste	5.30-6.36 N$/kg
Energy content of human waste	7 kWh/kg
Cost of crop residue	0.21 N$/kg
Energy content of crop residue	4.5 kWh/kg
Diesel generator efficiency	0.8
Steam turbine efficiency	0.54
Biodigester efficiency	0.2

4. Results

An Intel Core i5 64-bit 2.40 GHz computing system was used for computation. With a CPU solution time of 48 seconds, the demand profile and resource availability are matched to generate an optimal network for a total annual power demand of about 0.465 GWh for the 15 clients connected to the minigrid. The selection of the starting parameters is critical in determining the optimal solution. The case study result shown is for a scenario where the available SC resources are capped, while the available PV energy that can be supplied to the minigrid is left to be large enough to cover the deficit of the power demand of the locality. Power storage batteries are also available to buffer the intermittency of the power supply system.

The DES depends mainly on PV technology as it is the cheapest and uncapped energy source. Because of the intermittency of the PV supply, it is not able to meet client demand at all times of the day. The SC technologies are the next cost-effective technologies and are selected next to meet the demand of the DES. Within the SC, the fuel preference is for crop residue, fuel wood, animal dung, human waste and diesel. The selection of SC fuel preference is dependent on the cost associated with the fuels.

Figure 2 shows the average seasonal power supply of the SC technologies at different times of the day for winter, spring, summer, and autumn. The DES relies on the SC technologies mostly between 18:00 and 06:00 for all seasons.

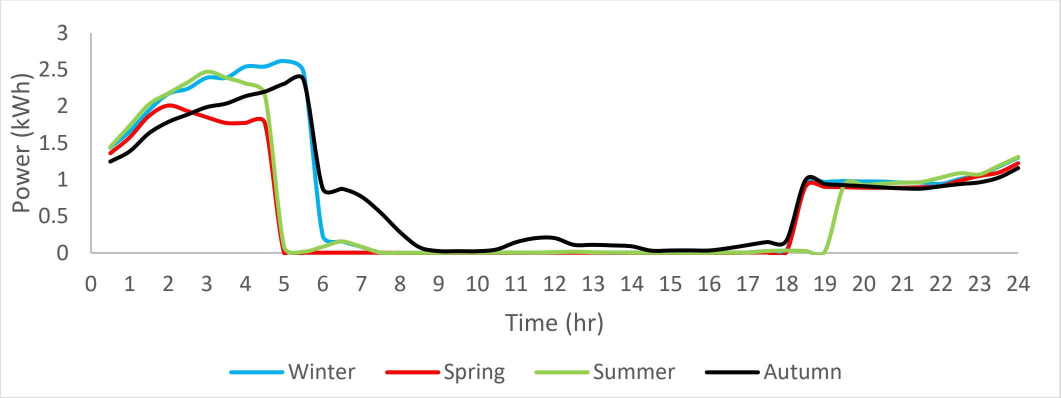

Figure 2: Average hourly seasonal power supply by the SC technology

Figure 3 shows the average PV technology energy supply at different times of the day for winter, spring, summer, and autumn. The PV units are selected to meet power demand in periods (between 07:00 to 17:00) when solar irradiation is available. Because of the intermittency of solar irradiation, it cannot be the sole energy source and must be matched with a storage battery or available SC resources to meet the demand, especially at periods out of the DNI peaks (17:00 – 07:00).

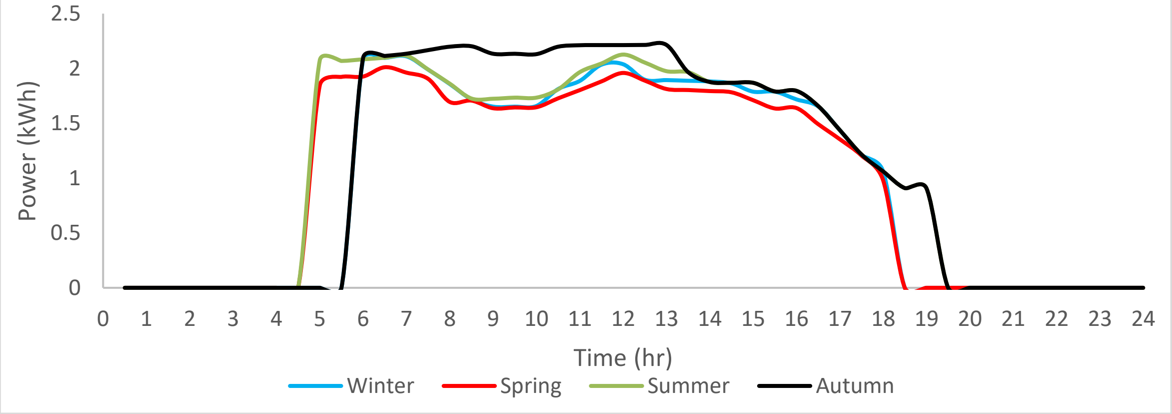

Figure 3: Average hourly seasonal power supply by PV technology

Not capping the available PV panel area allows the DES to use the PV technology when available generously. The PV supply is supplemented by energy from the SC feedstocks for times when solar irradiation is not sufficient to meet energy demand. The optimal use of the PV energy supply is attained when the average client demand profile mirrors the available PV energy supply. For this scenario, the TAC of the integrated network will be lower than the scenario where the power demand is higher than what the PV can supply.

The battery storage technology energy supply contribution to the DES is relatively small, with supply occurring only between 4:00 – 9:00 and between 13:00 -17:00. Within the optimum solution, the battery power supply is the least preferred technology. The capacity cost and operational and maintenance cost of the battery make it unfavourable for selection when there is a much cheaper option from the SC to cater for the intermittency of the PV power supply. For client profiles with high demand at night when the PV technology is not available for energy supply and the SC cannot meet all the demand, the battery technology is selected to meet the demand. This occurs at times between 4:00 – 9:00 and between 13:00 – 17:00. At these times, the battery is selected despite its high cost, as it is necessary to select it for the DES demand to be met. The SC resources are constantly available and used while neglecting the storage batteries if it is sufficient to meet the required demand because of their cost advantage compared to the batteries.

The SC energy conversion technologies selected were the diesel generator and the biodigester. The diesel generator was the most preferred as it has a high conversion efficiency and a low cost associated with power generation, as shown in Table 1. The steam turbine was not selected because of its relatively high cost of power generation. Although biodigester is a less efficient technology compared to steam turbines, it was selected due to its relatively lower cost. However, this would require more biomass resources to supply the same power compared to a similar DES, where the steam turbine is selected over the biodigester.

Table 2 shows the key model results obtained for the case study. For the demand profile given, the energy supply proportions are 42.7 %, 57.2 % and 0.0222 % for the SC, PV, and battery. The relative cost contribution of the SC is higher than its relative energy supply contribution, as shown in Table 2. Although the PV energy supply is cheaper than the SC, the optimal network contains the SC technologies for periods where the PV could not fully meet the DES energy demand. The battery technology was only selected when both the PV and SC technologies were not able to meet demand.

Table 2: Key model results

Quantity	Value
Total annualised cost (N$)	2,580,000
Annual operational cost of PV technology (N$)	23,900
Annualised capital cost of PV technology (N$)	130,000
Annual operational cost of SC technologies (N$)	173,000
Annualised capital cost of SC technologies (N$)	2,260,000
Annualised capital cost of the battery (N$)	66.3
Annual operational cost of the battery (N$)	44.1
Annual cost of animal dung (N$)	2,320
Annual cost of crop residue (N$)	2,150
Annual cost of fuel wood (N$)	9,230
Annual cost of human waste (N$)	42,300
Annual cost of diesel (N$)	96,251
% Cost contribution of PV unit	5.94
% Cost contribution of SC units	94.1
% Cost contribution of lithium battery	0.00427
% Energy contribution of PV unit	57.2
% Energy contribution of SC unit	42.7
% Energy contribution of lithium battery	0.0222
Total annual energy supply (GWh)	0.465
Energy cost (N$/kWh)	5.55

The minigrid cost is higher than the cost that would be incurred if energy was obtained from the main Namibian national grid. At the current Namibian electricity tariff of 4 N$/kWh, electricity from the grid would cost N$ 1,860,000 to produce 0.465 GWh, which is cheaper than that of the hybrid minigrid network. The hybrid network would require a government subsidy of 1.55 N$/kWh (39 %) to be comparable to the main national grid cost. Although the minigrid comes at a slightly higher cost, it comes with the advantage that it does not need long-range transmission installation costs while also creating local jobs. To improve the feasibility of the minigrid, the power plant size can be increased to cater for a larger scale (such as neighbouring communities) which allows the mini-grid to cover the overheads. The mini-grid power plant capacity factor can also be increased by considering more efficient energy conversion technologies. Finally, a centralised collection centre of biomass resources, especially the acquisition of encroached bushes from surrounding villages, can be considered to increase the available biomass resources in the SC.

5. Conclusions

The optimal DES for 15 clients with different demand profiles were selected. The PV-SC hybrid mini-grid coupled with lithium storage shows the potential to supply power to an isolated rural neighbouring community in Tsumkwe, Namibia. The selection of the case study parameter is critical in determining the optimal solution.

The case study considers a scenario where the SC raw materials are capped while the PV and batteries are uncapped to meet the energy demand of neighbourhood clients. The choice of the mix of optimal integrated SC superstructure depends on the power demand of each client, the cost and availability of energy resources, and the cost and efficiencies of the energy conversion technologies. The DNI for Tsumkwe shows tangible power supply potential but limiting because of its intermittency. Results show that the PV unit is always used to meet the power demand at most periods when there is sufficient direct irradiation. The SC sources were the preferred option to supplement the PV shortfalls because of their cost advantage compared with the solar storage battery. Battery technology was barely used. This case study shows the importance of incorporating the SC into the power network, which supports the intermittency of the PV supply because of the SC's constant availability. The TAC of the minigrid is N$ 2,580,000, with an overall annual investment and operational cost of N$ 2,380,000 and N$ 197,000. Introducing government tariffs, increasing plant size, and considering more efficient energy conversion technologies are recommended strategies suggested to improve the financial viability of the hybrid minigrid. Future work includes expanding the model to generate an optimal network for a larger community, incorporating heating into the energy network, studying the environmental-socio-economic impact of introducing modern power options to the community while considering several scenarios, and including more energy resources and power conversion technologies to the network. Biodiesel is a potential fuel option for some isolated communities that can be included to increase system sustainability but is not considered here due to the lack of oil-based feedstocks in the locality. With this model, future load profile forecasts could also be explored for mini-grid planning purposes.

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