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Integrated Off-Grid Resource Sharing and Energy Network Optimisation for Several Co-Located Rural Communities in Namibia

Kemi Jegede[a,*], Adeniyi J. Isafiade[a], Michael Short[b]

[a]Chemical Engineering Department, University of Cape Town, South Africa
[b]Chemical and Process Engineering Department, University of Surrey, Stag Hill, Guildford GU2 7XH, UK
kjegede@nust.na

This work develops a mixed-integer linear programming (MILP) optimisation model for reduction of total annual cost (TAC) and associated carbon emissions for several neighbouring communities (prosumers) within a region sharing resources for off-grid hybrid power generation. Hybrid power caters for the intermittency of renewable energy sources, ensuring sufficient and reliable power supply. The off-grid hybrid power network comprises photovoltaic (PV), lithium batteries, diesel generator, as well as several supply chain biomass resources and technologies generating power for a region of neighbouring communities. The biomass resources available includes animal dung, human waste, crop residue, and fuel wood. A biomass gasifier and steam turbine are technologies available for biomass power generation. Resource sharing ensures a more holistic network optimisation that promotes economies of scale of power conversion technologies. Excess energy generated by a community can be transferred to one or more communities within the region. This has the potential to reduce the integrated network's overall cost and carbon emissions. For the case study considered, which comprises seven co-located communities, results show levelised cost and carbon emission reduction of up to 61.6 % and 73.6 % respectively when resources are shared, compared to single community power generation.

1. Introduction

Namibia, has large energy deficits with about 70 % of its energy imported from neighbouring countries (Nampower, 2023). The country has industrialisation plans which will increase energy demand (Lukonga, 2024). Rural communities that are currently unelectrified are at risk of being excluded in the country's development plans and being sidelined from industrialisation due to their remote location and distance from grid infrastructure. There is a need for Namibia to have sustainable energy to promote fulfilling the country's development goals.

Power systems sharing has been found to improve optimisation by reducing costs and environmental impacts (Krishna et al., 2024). It can also improve local supply-demand balancing, reduce voltage deviations, and improve social welfare (Herenčić et al., 2022). Additionally, power systems sharing gives maximum reliability and quality of energy, where each customer is a potential prosumer (Razavi et al., 2024). A systematic review of power systems resource sharing models classifies the most common methods into 6 categories: double auction theory, blockchain technology, game theory, machine learning, optimization strategies, and other models' categories. Table 1 shows the outlines some of the methods used for power sharing.

This work covers gaps highlighted in literature listed in Table 1. Hybrid resources and conversion technologies were considered, looking at energy sharing within co-located energy communities. The objective of this study is to use an MILP optimisation strategy to determine the cost and carbon emission reduction that would result from co-located communities sharing resources and an energy network to meet all clients' energy demands. This would be done by modelling individual community demand and comparing model results with a model where resource sharing between the individual co-located communities is available. The MILP approach has the advantage of simplifying complex systems. MILP is also a favourable method for this case study with little community-specific data. The novelty of the current work stems from 1) the comparison of individual community's TAC and associated carbon emissions with those obtained when resource and energy is shared

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in a coalition of seven communities, 2) Considering the supply chain parameters associated with procuring resources from multiple locations, and 3) Application of models to an existing Namibian region of communities, the Otjozondjupa region. Integrated off-grid resource sharing and energy network optimisation among the communities within the region is expected to have cost and environmental impact benefits.

Table 1: Comparative summary of literature findings

Reference	Model type	Scale	Real (R)/Hypothetical community (H)	Hybrid energy technology	Energy sharing	Biomass resource use considered
Billal et al. (2025)	Mixed-integer MINLP	Plant size	R	×	✓	✓
Herenčić et al. (2022)	MILP	Tech-park, kindergarten, and library	R	×	✓	×
Jegede et al. (2023a)	MILP	5 houses	R	✓	✓	✓
Jegede et al. (2023b)	MILP	1 community	R	✓	✓	✓
De Mel et al. (2024)	MILP and MINLP	Air source heat pumps and hot water storage tanks	H	×	×	×
This study	MILP	Seven co-located communities	R	✓	✓	✓

2. Problem statement

Off-grid electrification is proposed for communities in the Otjozondjupa region in the northeast of Namibia. An energy storage and distribution grid supply energy provided by several communities to clients within the region. The seven co-located communities in the energy sharing scheme have various population sizes which directly determines the power demand amount. The power technology options available for optimisation are the PV panels, lithium storage batteries and supply chain technologies. The supply chain technologies comprise diesel generator, steam turbine as well as biodigester. The diesel generator uses diesel resources, the biodigester uses only fuelwood (as specified by the technology manufacturer), while the steam turbine can utilise diesel as well as biomass resources namely crop residue, human waste, animal dung and fuel wood.

Within each of the seven communities, there are varying available resources with corresponding energy conversion technologies available for selection. The resources common to all communities are solar irradiance, diesel and human waste. Energy conversion technologies available to all communities are PV, lithium batteries, diesel generators and steam turbines. Tsumkwe is the only community that contains farmlands and has vast open land with natural vegetation. Tsumkwe also has fuelwood, crop residue and animal dung biomass resources, and consequently has the option for a fuelwood gasifier available for selection.

Power resource's locations are independent from demand clients' location. Two scenarios were considered and compared. The first scenario considers individual community loads without energy sharing. The second scenario considers energy sharing between communities. For the energy sharing scenario, Tsumkwe is selected as the central hub because of its accessibility to all biomass resources and consequently an option to generate power using all available conversion technology. The results of decentralised facilities were compared with the results of centralised facilities. The benefits that can be attained from energy sharing are grid resilience, the use of power provided from resources and/or technology that are not within the community, and economies of scale. Economies of scale consequently reduce TAC and carbon emissions. The goal is to reduce TAC and subsequently reduce environmental impact by introducing energy sharing within co-located communities.

3. Methodology

The methodology is an extension of Jegede et al. (2023b) where an optimal match of the energy supply to demand zones are determined based on hourly and seasonal time discretisation. Four seasons are considered, namely winter, autumn, summer, and spring, with averaged demands within each season used to design the system. The objective is minimisation of the TAC as shown in Eq(1).

$$TAC = C^{CC} + C^{OP} + C^{CE} \tag{1}$$

The operating cost comprises the maintenance cost of each technology, the resource purchase cost and the resource transportation cost to locations of respective conversion technologies. For the capital cost, an interest rate of 7.5 %, project lifetime of 20 y, giving a capital recovery factor value of 0.0981, are used. Carbon emission is a combination of emissions during supply chain resource transportation and power generation from diesel. Power generation using biomass resources are considered to be carbon neutral. For the case of energy sharing within communities' case, all technologies except the PV and diesel generator are centralised in the Tsumkwe plant where power is generated and shared amongst respective communities. The PV and diesel generator power conversion technologies are located within respective communities. The key parameters used in this study are as reported in Jegede et al. (2023b).

Eq(2) shows the operating cost, which comprises the maintenance cost of each technology, and the cost of procuring resources from the supply chain. The cost of procuring the supply chain resources includes the resource purchase cost and the cost of transportation of resources from various locations to the mini-grid.

$$C^{OP} = C^{OPM} + C^{CPR} + C^{OPT} \tag{2}$$

where C^{OPM} is the annual operating cost of maintaining units [$/y], C^{CPR} is the annual cost of purchasing supply chain resources [$/y], and, C^{OPT} is the annual cost of transporting supply chain resource to the mini-grid [$/y].

Eq(3) shows the supply chain total unit maintenance cost.

$$C^{OPM} = \sum_{p=1}^{P} \sum_{t=1}^{TD} \sum_{j=1}^{J} \left[C_j^O \times EU_{j,t,p} \right] \tag{3}$$

The total unit maintenance cost is obtained by multiplying each units' maintenance cost (C_j^O) [$/kWh], with the amount of energy generated by the respective unit ($EU_{j,t,p}$) [kWh]. The indices $j \epsilon J$, $t \in TD$, and $p \epsilon P$ represents the power conversion unit, the daily time discretization, and the number of seasons in a year respectively.

Eq(4) shows the cost of procuring supply chain resources:

$$C^{CPR} = \sum_{p=1}^{P} \sum_{t=1}^{TD} \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{h=1}^{H} \left[CR_i \times M_{h,i,j,t,p} \right] \times N^{days} \times \Delta t \tag{4}$$

where CR_i is the cost of each resource [$/kg] or [$/l] in the case of liquid resource, and $M_{h,i,j,t,p}$ is the amount of each resource i from location k used by the supply chain conversion technology i [kg/hr] (or [l/hr] in the case of liquid resources). N^{days} is the number of days in the season, Δt is the time interval used.

Eq(5) shows the supply chain resource transportation cost:

$$C^{OPT} = \sum_{p=1}^{P} \sum_{t=1}^{TD} \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{h=1}^{H} \left[T \times M_{h,i,j,t,p} \times D_{h,i} \right] \times N^{days} \times \Delta t \tag{5}$$

where T is the constant transportation cost [$/km/kg], and $D_{h,i}$ is the distance between each resource location and the mini-grid [km].

Several supply, demand, linkage, capacity, and binary variables were incorporated into the model to define the solution space. These constraints are namely, 1) matching power demand and supply, 2) defining the amount of each resources available and capacities of each power conversion technologies, 3) ensuring that sufficient resources are sent to respective power conversion technologies, 4) ensuring that only the PV power generated is used to charge the batteries, 5) ensuring that power generated by each technology is not more that the rated capacity of the technology, 6) controlling the depth of discharge and charging of batteries, 7) ensuring that the capacity of each unit technology remains the same for all seasons, and, 8) specifying resources and associated conversion technologies available for power generation at each community.

The MILP model was developed in the Pyomo algebraic modelling environment (Bynum et al., 2021) and solved using the CPLEX solver (IBM, 2022). The model comprises resources from several locations sent to meet the supply of several power technologies in respective communities. Sixteen farms around Tsumkwe with known distances were identified to supply fuelwood, crop residue and animal waste to Tsumkwe location. In each of the farms, the resources available were determined to be 1,400 t/y fuelwood and 30,000 t/y crop residue. The Tsumkwe community load profile is not available, so the Kenyan load profile for rural communities as defined by Li et al. (2018) was adapted. It defines various client categories (household, industries, and services), keeping account of the number of people within the community.

Optimisation results obtained when resource sharing is allowed between communities is compared to results of individual communities without resource sharing to determine the cost and environmental impact benefits of resource sharing.

4. Results

Each community was optimised separately without considering grid connections between them, followed by a model that combined all seven communities and allowed resource sharing available from central Tsumkwe.

Transportation of resources between communities was not considered. An intel Core i5 64-bit 2.40 GHz computing system was used for computation. Table 2 shows the solution information for the models. All individual community without resource sharing have similar model formulation.

Table 2: Solution information for the decentralised and centralised scenarios

Model type	Solution time [s]	Constraints	Integer variables	Continuous variables
Tsumkwe	50.6	83,224	2,012	98,565
Grootfontein	44.7	83,224	2,012	98,565
Okahandja	38.0	83,224	2,012	98,565
Okakarara	42.2	83,224	2,012	98,565
Omatako	46.4	83,224	2,012	98,565
Otavi	42.7	83,224	2,012	98,565
Otjiwarongo	43.0	83,224	2,012	98,565
Resource sharing	65.4	106,292	2,796	107,049

The individual community power supply without power sharing is shown in Figure 1(a). For all individual community models (except Tsumkwe), one steam turbine with capacity of 500 kW (and using human waste feedstock) is selected. For Tsumkwe, the gasifier (two, with a capacity of 49 kW each) is the supply chain technology selected. This technology is possible only for Tsumkwe where there is vast open land to gather fuel wood resource for the gasifier.

Combined community power supply by different power conversion technologies is shown in Figure 1(b). Technologies selected are one 68 kW gasifiers (G3), two 300 kW gasifiers (G4), two 100 kW diesel generator (DG3), one 500 kW steam turbine (ST1) and 776 PV panels with a capacity of 0.25 kW each.

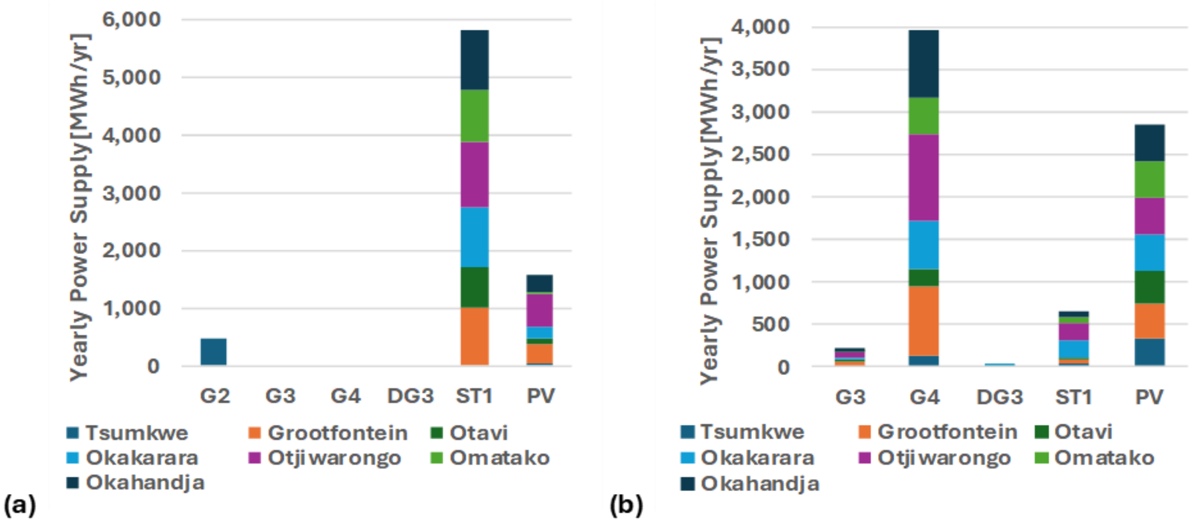

Figure 1: (a) Yearly power supply without power sharing; (b) and yearly power supply with power sharing in Otjozondjupa Region.

Power supplied for all scenarios considered is dominated by supply from the supply chain technologies (gasifier, diesel generator and steam turbine), with a smaller fraction supplied by the PV technology. The demand profile adapted show that the total power consumption is highest at off-peak times for the PV technology power supply, resulting in more reliance on the supply chain technologies. PV power supply is a preferred option for supplying dispatchable power over the use of batteries, reflected in the optimal technology selected never including the batteries to meet power demand. Each individual community without power sharing (except Tsumkwe) does not have an option to use the gasifier technology, as the fuelwood resources required to fuel it is not available in these communities. Consequently, the steam turbine is selected for individual communities, making use of human waste which is the only biomass resource available outside of Tsumkwe. The steam turbine works by direct combustion of biomass, providing heat to the steam boiler that provides steam to move turbines connected to generators, subsequently generating electricity. For Tsumkwe, the supply chain technology selected is the gasifier, making use of available fuelwood which is not available in any other community. The diesel generator and the storage batteries were not competitive for selection in any of the individual community models. Similar to the individual community power supply results, power in the combined communities resource sharing model is predominantly supplied by the supply chain technology because of the client demand profiles. Seasonal variations in power supply from different technologies are shown in Figure 2.

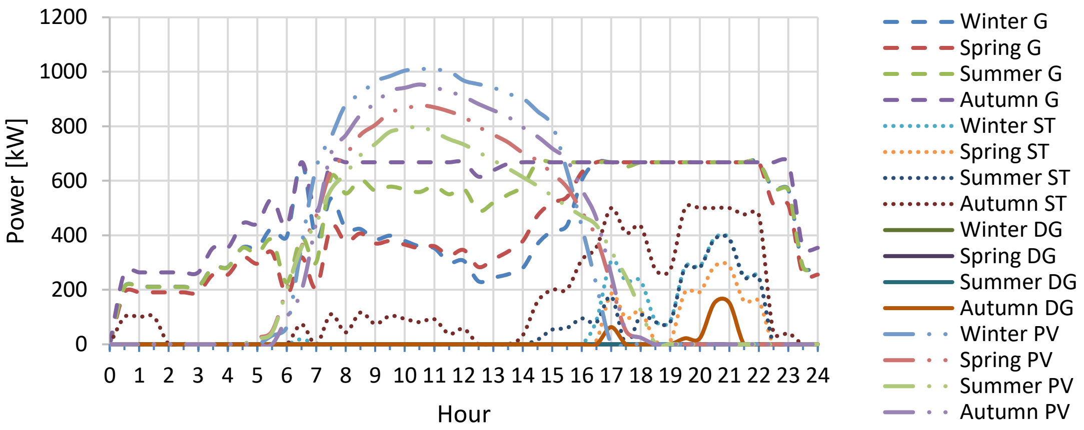

Figure 2: Representative daily seasonal gasifier (G), diesel generator (DG), steam turbine (ST), and PV power supply for the Otjozondjupa Region.

PVs supply power between 06h00 and 16h00, and the supply chain technologies meet demand at times when power supply from PV technology is not viable.

The trade-offs of resource sharing in each individual community compared to the combined region resource sharing power supply is shown in Figure 3. TAC reduction ranges from 42.3 % to 61.6 % and 35.28 % for Tsumkwe. Carbon emission reduction ranges from 65.1 % to 73.6 %. The sum regional carbon emission is 54.5 t with resource sharing and 166 to without resource sharing. There is no carbon emission benefit for Tsumkwe because the selected gasifier has lower carbon emission compared with the steam turbine which is selected for all other communities and for the energy sharing scenario. The gasifier is however, not available for all other communities' individual model because these communities do not have woodlands with vegetation for fuelwood. For large energy demand, the steam turbine is more cost effective than the gasifier but having more carbon emissions than the gasifier.

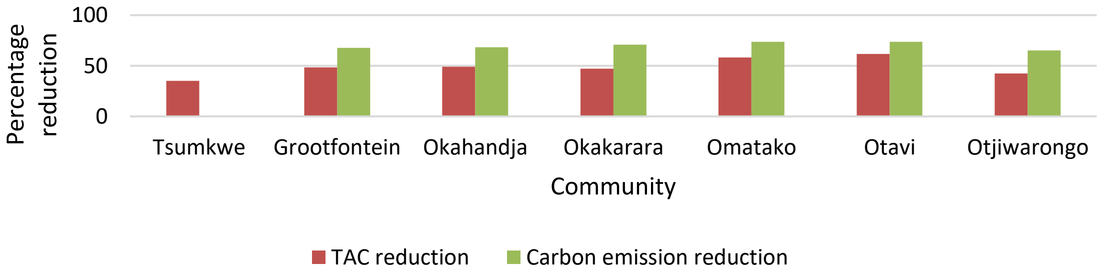

Figure 3: Reduction in TAC and carbon emissions due to resource sharing

Carbon and TAC reduction benefits are as a result of the economies of scale when resource sharing is available. The sum of the regional TAC is $ 482,714.88 with resource sharing and $ 987,909.19 without resource sharing. Economies of scale makes the resource sharing model more economic than individual communities generating their own power and being limited to resources available only within the community. Overall carbon emission is also reduced in the resource sharing and energy optimisation within Otjozondjupa region.

5. Conclusions

Integrated off-grid resource sharing for the energy network of seven neighbouring communities within the Otjozondjupa region, Namibia is modelled using MILP optimisation considering the total annualised operating, capital and carbon costs. Results show that for the non-combined case, the fuelwood gasifier is selected in the Tsumkwe community where fuelwood resources are available. This is couples with the PV power supply to meet the Tsumkwe community's power demand. For all other communities where fuelwood is not available, human waste is the selected supply chain resource, making use of the steam turbine power conversion technology. This is also coupled with the PV power supply to meet individual communities' power demands. Resource sharing for the combined seven communities allows the use of power supplied from using fuelwood in communities where fuelwood is not available. It also has the advantage of reduction in levelised power costs and amount of carbon emissions by 61.6 % and 71.6 % respectively. The sum of regional TAC is $ 482,714.88 with resource sharing and $ 987,909.19 without resource sharing. The sum regional carbon emission is 54.5 t with resource sharing and 166 t without resource sharing. This is a particularly favourable finding for Namibia which has large energy deficits and heavily dependent on import of power to meet its demand. Despite the benefits that come with integrated off-grid resource sharing within a region, information sharing between these communities and infrastructure extension to accommodate resource sharing are challenges that should be addressed. Regulatory policies and control strategies can help reduce potential security risks due to information sharing. The cost associated with transmission cables was not considered in this work. Future work could include associated infrastructure cost of the information and resource sharing costs. Two separate models were compared in this study. A combined model having both resource sharing and individual community technology can be developed where the optimal network is selected considering transmission cost. The model can also be further extended to incorporate the water-energy-food nexus within the draught-stricken region battling hunger crisis.

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