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Simulating the potential of swarm grids for pre-electrified communities – A case study from Yemen

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Abstract:

Swarm grids are an emerging approach to electrification in the Global South that interconnects individual household generation and storage to a small electricity network to make full use of existing generation capacities. Using a simulation tool for demand, weather, and power flows, we analyse the potential of an AC swarm grid for a large pre-electrified village in rural Yemen. Service quality and financial indicators are compared to the cases of individual supply and a centralised micro grid.

While the swarm grid would improve supply security from the current 12.4 % (Tier 2) to 81.7 % (Tier 3) at lower levelised costs, it would be inferior to the micro grid in both service (Tier 4) and costs. This is mainly driven by the large pre-installed fossil-fuel generator and storage capacities in our case study. However, this situation may be representative for other relevant locations. Under these conditions, a swarm grid poses the danger of creating (possibly-undesirable) incentives to invest in diesel generators, and it may fail to support prosumerism effectively.

Nevertheless, the swarm's evolutionary nature with the possibility for staggered investments (e.g. in smaller yet complementary groups of consumers) poses a central advantage over micro grids in the short-term alleviation of energy poverty.

Keywords: Swarm electrification, swarm grid, micro grid, energy access, distributed generation, Yemen

∗The views and opinions expressed in this article are those of the authors and do not necessarily reflect the position of any of their institutions.

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1 Introduction

Over 1.1 billion people worldwide still suffer from electricity poverty, and, while only 4 % of the urban population do not have access to electricity, 27 % of worldwide rural communities are affected [1, p. 114]. An extension of the national grid will be the best option for urban and 30 % of rural areas, but a major share of rural areas may be provided off the grid [1, p. 12, 2]. There is a manifold of different approaches (see e.g. [3] for a recent survey of prominent systems) towards rural electrification:

A traditional **grid extension** offers unlimited electricity and inherits the quality of a national grid. However, construction can be lengthy and expensive, particularly for remote areas or difficult terrain. Also, outages or other shortcomings of the national grid are inherited directly and might result in limited electricity access despite the interconnection.

Individual solutions are mostly fuel generators and solar home systems (SHS), consisting of solar photovoltaic (PV) panels and a battery. Scalability and simplicity lead to low prices that can be affordable even for households outside higher income classes. Historically, diesel generators were the most common type of system [4,p. 6], but SHSs have seen a sharp rise due to quickly decreasing prices. An individual supply solution is not necessarily designed to meet the household's demand, and a mismatch can result in either unused capacities or lost load. Therefore, prospects for individual solutions are often limited.

Micro grids are tailored to meet local demand, but they require professional planning and large upfront investments that prove infeasible for many communities. Nevertheless, hybrid micro grids (renewables and fuel-based generators combined) are the least-cost option for sufficient electrification in many cases, outperforming grid extensions [5, 6]. Installations undertaken previously are often not taken into account and considered sunk investments or stranded assets. Yet, this is also the fate of the micro grid in cases where a national grid interconnection is due, potentially discouraging prospective investors [7, 147f].

In contrast to that, **a swarm grid** may provide the advantages of a grid extension or micro grid in the long run, but without requiring the significant upfront investment. The emerging approach proposes the interconnection of decentralised individual supply units to a network. This promises an improvement in electricity services for communities that are pre-electrified through ownership of low-capacity individual supply units: Complementarity in generation capacities and demand patterns allows consumers to benefit from sharing their individually-produced electricity. This enables them to reach a de-facto higher standard of electricity services without (necessarily) installing new capacities.

As illustrated by Figure 1, over time, the swarm grid evolves from a smaller network of households to a local grid. Including previous installations prevents asset stranding, and an increasing number of households and generating units enhance the network via bottom-up action. The network would eventually grow into a mature grid with high service quality and could be interconnected with the national grid one day.

Benefits of swarm grids are not limited to supply improvement, but advocates see them as a chance for social development and democratisation. Households remain independent in their investment and supply decisions and become prosumers [8, 9], i.e. they become involved in the generation, storage, and distribution of electricity. This empowerment of the bottom of the pyramid makes citizens (in rural areas) more responsible [10, 11]. Establishing electricity trading as a new form of income and engaging households and local stakeholders in service infrastructure may boost social and economic development [8].

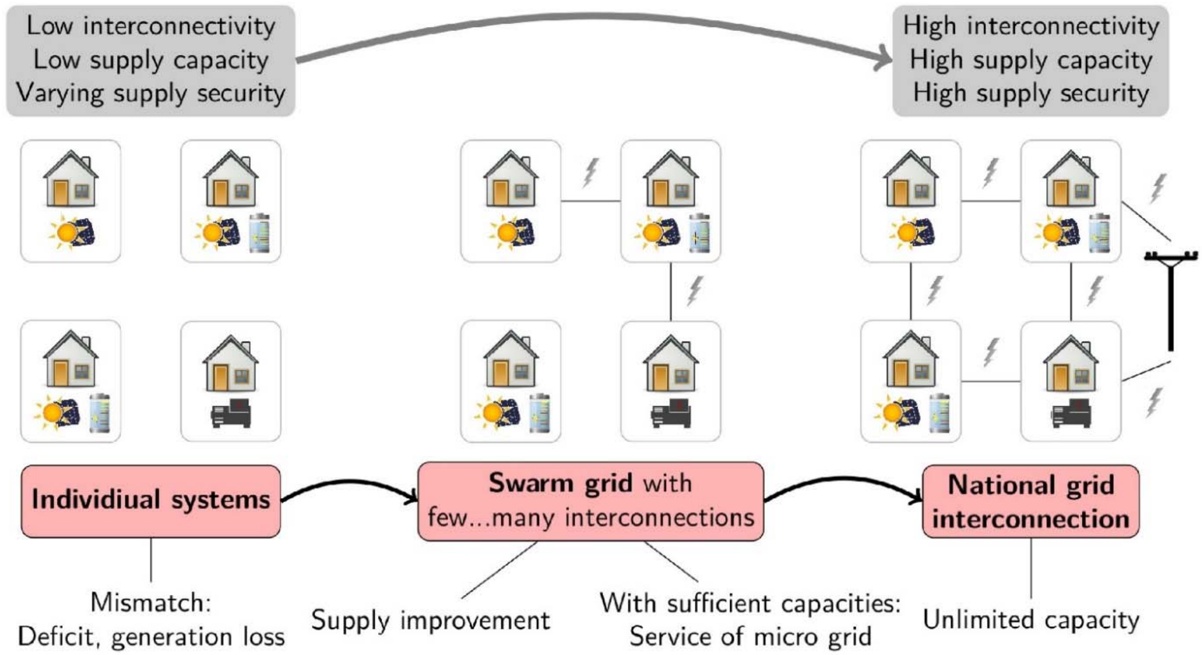

Figure 1: Swarm grid evolution and its potential to improve supply

Swarm electrification is the subject of a growing body of literature. Two early examples for studies on the swarm concept are given by [12] and [13], which examine the potential and electrical design for organically grown DC micro grids as the interconnection of individual supply. A formal introduction of swam electrification is given by [14], which elaborates the conceptual framework of swarms and their potential to overcome the shortcomings of micro grids (including a brief financial analysis of a case study in Bangladesh). [15] adds to that by providing an account of the system of swarms as well as its chances and challenges. The study names population density as a crucial variable and refers to future investigations to examine whether swam electrification holds potential for low-density regions as well. [16] and [17] are further reviews of swarm grids in general and the case of Bangladesh in particular, confirming their potential in the provision of (affordable energy access). [18] envisions swarm electrification as a major driver in the provision of universal energy access in Sub-Saharan Africa.

The strongest motivation for swarm grids is illustrated by [19] through the quantification of the excess energy of individual supply in Bangladesh, which exceeds 30% of local electricity generation. Moreover, [20] develops a list of success factors for decentralised renewable energy networks from an assessment of cases in Germany and the Global South. The authors confirm that swam electrification is in line with these factors, but they admit that the affordability of energy is the probably most crucial factor in the Global South. [21] compares individual supply, micro grids, and swarm grids regarding market suitability, technical appropriateness, and user-centeredness based on a literature review and case studies. The authors identify swarms as the superior mode of electrification, but they hint at potentially lower costs for a micro grid, and the lack of a thorough quantitative analysis limits explanatory power. [22] provides a comprehensive qualitative overview of the potential benefits of swarm electrification over individual supply (i.e. the mitigation of volatility, increased reliability, financial flexibility, the connection of new customers without generation, and flexible investment), but they also cite concerns about missing system combability, losses increasing in the distance, and issues of commercialisation.

Some analyses also consider the technical dimension of swarm grids. [23], for instance, develops a decentralised control architecture for swam grids and validates its efficacy. [24] models swarm grids using semi-explicit differential algebraic equation systems to derive control objectives. [25] analyses the performance of a swarm grid using passive droop control, and [26] uses probabilistic models to analyse stability.

Peer-to-peer (P2P) grid is yet another term for the interconnection of prosumers that is often used in developed countries and the context of the energy transition. [10] provides an overview of the concept and its social dimension, and [27] confirms the different benefits of P2P trading among prosumers. [28] and [29] use a linear optimisation model and a multiagent simulation, respectively, to validate and quantify some of the benefits to P2P grid infrastructure for the case of communities in the UK. [30] provides a general review of P2P trading projects and emphasises the consideration of necessary communication and control networks for future research as opposed to a focus on the efficacy of business models.

However, quantitative assessments of swarm grids (particularly for the Global South) are still rare, and especially the comparison of swarm grid to other methods of rural electrification lacks numerical evidence. Moreover, and to the best of our knowledge, there has been no study that considers either the Middle East as an application area for swarm electrification or an AC approach to it. On the contrary, previous literature has focused on DC swarm grids (see also [31, 32]), typically citing reasons such as high conversion losses in solar-based off-grids as a reason do disregard AC [33].

Nevertheless, AC might be preferable for some reasons. DC approaches have been limited to low-voltages to prevent danger and save electrical equipment, thus implicitly capping generation and long-term services. A standard-voltage AC grid may allow a more flexible and secure system of distribution. Also, most household or business appliances will require AC. Hence, especially for villages with pre-existing AC devices, DC is hardly an option.

Therefore, this study assesses the potential of a 230 V AC swarm grid in the case of Bayhan A'mas Aljabal, a pre-electrified community in rural Yemen. Located in the southern part of the Arabian Peninsula, the country suffers from energy poverty, undersized generation capacity, and low rural electrification rates [34, 35]. However, previous studies have shown a significant potential for off-grid systems in rural Yemen [36, 37].

The study adds to the scientific and technical discourse in three crucial points: First, the article gathers numerical evidence on the technical and financial prospects of swarm grids in the Global South with an own simulation tool. Secondly, this study is the first application of swarm electrification to a case study in the Middle East. Lastly, and most importantly, this work investigates the novel concept of AC swarm electrification.

A Python-3-based tool simulates weather (and, thus, generation), demand, and power flows to compare three different electrification solutions: Individual supply, a swarm grid, and centralised micro grid (see Section 2). For each scenario, the study assesses the system's potential to supply the intended demand (via supply security and generation losses) as well as its costs (via levelised costs of electricity, net present value, and breakeven costs for grid extension). Data was taken from a household survey (see Section 3) as well as numerous technical studies and market research. Additionally, the simulation is aided by an optimal energy mix (OEM) program.

The results (see Section 4) show that a swarm grid can improve supply security from 12.4 % in the individual supply scenario to 81.7 %, improving electricity supply at $LCOE$ of 29.4 €ct./kWh. However, a micro grid offers higher supply security of 97.6 % at an even lower cost of 23.1 €ct./kWh. Depending on geographical factors, both systems can be cheaper than a grid extension, with breakeven grid extension costs of 17 €/km (micro grid) and 18.8 €/km (swarm grid).

In our study, the substantial benefits of a swarm grid can be mostly attributed to existing (fossil fuel) generators that could be run on higher load factors and supply customers without their own dispatchable generation (see Sections 5 and 6). PV systems, on the other hand, did not contribute significantly to this effect, as initial storage capacities were already oversized. This is opposed to other studies, which cite large PV generation losses in individual supply as the main driver for swarm grid benefits [14, 19, 22]. The superiority of a micro grid, in turn, results from the OEM-approach, which chooses more cost-efficient capacities than consumers have done thus far. Although these results depend entirely on the parameters of the case study, the situation may be representative of a number of pre-electrified communities, whose generation and storage portfolio might typically not be sized optimally. The study also hints at the potential of strategic scheduling of generation and storage by the swarm grid controller, solidifying our conclusion towards the benefits of planned or at-least aided grid design. Also, tariff design, setting (dis-)incentives for owners of generation units, and effects on social development will be important issues to consider for the future.

2 Simulation tool and assumptions

This study uses a simulation tool in the open-source programming language Python 3, working with a multitude of input data specified in an Excel data sheet. The simulation analyses the performance and costs of the different supply solutions individual supply, swarm grid, and micro grid. Figure 2 shows a flow chart outlining the program.

The tool simulates a time series with one-hour steps, covering a whole year. This time series includes variations in demand, weather, and resulting power flows that occur on an intra-day, inter-day, and intra-annual basis. As an individual solution and swarm grid focus on distributed systems, each consumer has to be simulated individually. However, in the case of a micro grid, consumers and power generation can be aggregated.

First, each consumer's demand and the specific generation of PV panels are simulated for each time-step. Based on the type, number, and turn-on probabilities of the electric devices owned by consumers, a randomised demand profile is estimated. Global irradiation is generated with Python 3 library pvlib [38] and input values for the monthly local cloud cover factor. The tool uses day and night temperatures on a monthly basis to calculate specific PV generation. To account for volatilities, white noise of 15% is added to both temperature and cloud cover profiles in each time-step individually.

Subsequently, the tool simulates power flows. For the micro grid, an optimal energy mix (OEM) is determined in advance (see Appendix A.1). In general, for supplying demand, the tool treats PV generation as preferred, followed by battery discharge and diesel generator. Surplus generation can be stored in batteries, when available. Performance indicators, i.e. supply security and generation efficiency, as well as financial indicators (net present value, levelised costs of electricity, breakeven costs for a grid extension) are then computed based on the results.

2.1 Scenarios

The article assesses the potential of a swarm grid by comparing supply and costs with alternative supply solutions, namely the current system of individual supply and a micro grid. The three cases are defined as follows:

Individual supply (IS): Only the existing, private generation units provide power for each consumer individually. Consumers are not interconnected, and diesel generators are not shared. No additional investments in control units or inverters are made, and the current systems operate on their present parameters. Existing capacities are replaced entirely when they exceed their lifetime. This scenario is treated as a base case.

Swarm Grid (SG): Existing generation and storage capacities are interconnected. Individual household demand is primarily met by the household's own devices, while the grid is used when a local mismatch occurs. All capacities are replaced completely when their lifetime ends. Figure 3 visualises the algorithm that determines the power flows for the SG scenario.

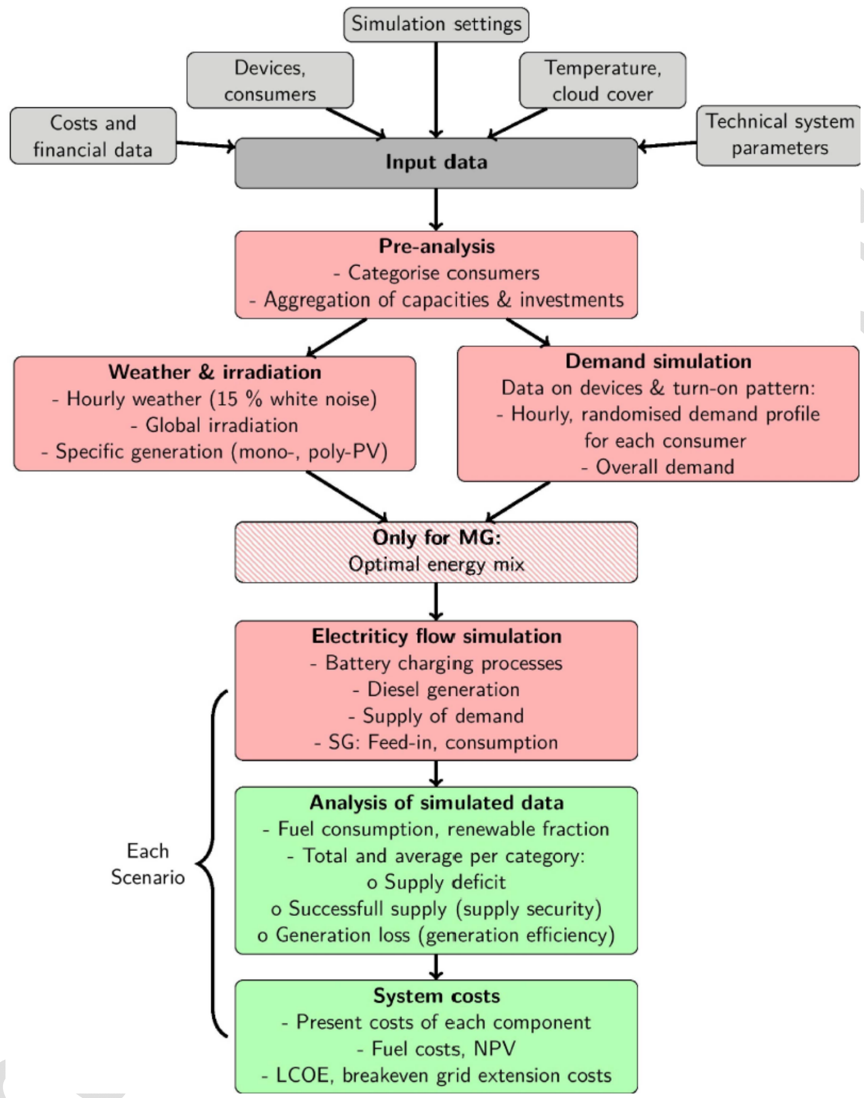

Figure 2: Flow chart of the simulation tool

In the case of excess supply (due to full storage capacities or fixed steps for generation control of the diesel generator), power can be shared with the local grid (feed-in), subject to distribution losses. To promote a feed-in and avoid low efficiencies for charging, the batteries charge up to 90%. In the case of excess demand (i.e. lost load in individual supply), consumers may be supplied from the grid, if sufficient feed-in is provided. Only if excess demands cannot be covered with the present feed-ins, are unused generation capacities of the diesel generators activated for additional generation. However, in a swarm grid, optimal coordination of the decentralised generation units demands complex control mechanisms. Its system interactions depend on the swarm grid controller design. Here, all prosumers are granted equal income opportunities in feed-in.

Micro Grid (MG): A joint demand for the whole village is supplied using centralised generation and storage capacities. Ex-ante, an OEM program determines optimal capacities, based on average daily demand and solar irradiation (see Appendix A.1). Existing capacities will be excluded from the planning process. In contrast to the other scenarios, households appear as pure consumers that do not actively interact with generation or supply, which is why variables can be aggregated for the whole village. During performance evaluation, demand will be lowered by the generation of existing PV panels, as owners may still rely on their devices and self-supply. Existent batteries will not be used. Thus, the micro grid will encounter a lower demand in its first years of operation and can appear to be oversized. Investment costs for the existent generation units are not considered.

2.2 Performance indicators

The study compares the different scenarios regarding their performance in service provision using two indicators. Both evaluate the base year; hence, demand growth is not considered in either.

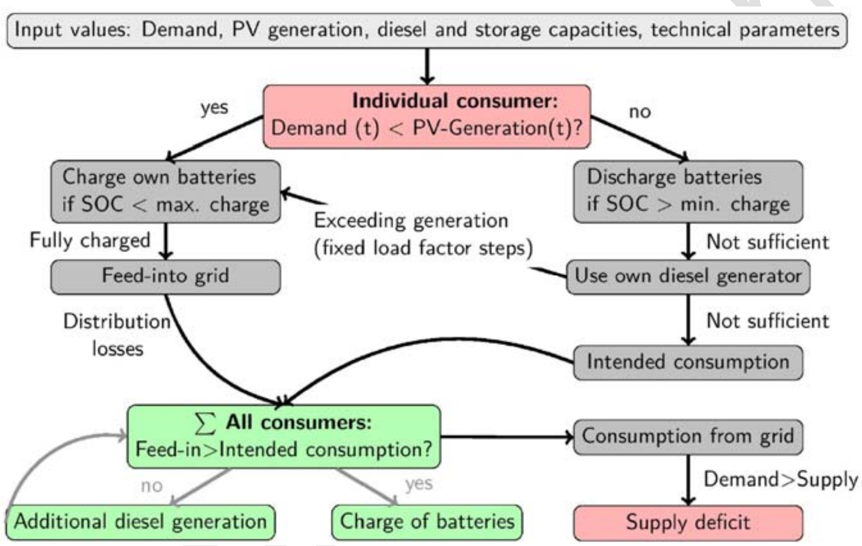

Figure 3: Flow chart of the power flow algorithm for the swarm grid scenario

Supply security indicates the potential to meet consumer demand E_{dem} with a successful supply E_{ss}. A supply security of 100 % would imply a successful supply at all times.

$$Supply\ security = \frac{E_{ss}}{E_{dem}}$$

Generation loss represents the generation that remains unused E_{loss} as a share of the overall generation E_{gen}. Generation losses take place when batteries are fully charged and cannot store any more excess generation, or due to fixed load factor steps for the diesel generators without the possibility of storage. In the SG, unused feed-in is accounted for as generation losses.

$$Generation\ loss = \frac{E_{loss}}{E_{gen}}$$

In the MG scenario, the indicators are computed for the aggregated grid right-away. In IS and SG scenarios, the indicators are first computed for each household individually. Overall indicators are then defined as the unweighted average of individual indicators. This ensures the absence of a bias due to sizing effects; e.g. in the case of supply, the weighted average, which is equivalent to the ratio of overall supply and overall demand, could exhibit high values even if a single but large consumer manages to supply himself while a large majority of consumers could even have a supply security equalling zero. In other words, a weighted average would focus on the size of consumers but would conceal the effect of their number. The approach of an unweighted average is equivalent to normalising each consumer to a unit demand / generation and then considering aggregated indicators. Hence, the method resembles a rather Rawlsian approach to evaluating the grid that prioritises equality in energy access.

2.3 System costs

Three annuity-based financial indicators compare each solution's cost: Net present value (NPV), levelised costs of electricity ($LCOE$) and breakeven grid extension costs. They are based on an estimation of investment and operation costs in order to provide electricity for a given time horizon (henceforth referred to as project).

The NPV represents total discounted costs. This includes replacement costs for components whose lifetime ends during the project lifetime, residual values at the end of the project, and transport as well as fuel costs. Installation and O&M costs are neglected.

Capital costs for each scenario are calculated from the investment costs for main system components, including transport costs. The investment for any component i in the first year, C_i is calculated from its capacity CAP_i, its costs per unit c_i, and its transport costs $p_{transport}$ specific to its weight m_i:

$$C_i = CAP_i \cdot (c_i + p_{transport} \cdot m_i)$$

Then, including the costs of k replacements within n years, a residual value C_i, res, a project lifetime T , and a nominal interest rate d, the present value of capital costs for any component NPV_i can be expressed as:

$$NPV_i = C_i + \sum_k^k \frac{C_i}{(1+d)^n} - \frac{C_{i,res}}{(1+d)^T}$$

Operational expenses, in this case, are only based on fuel consumption q_{fuel} of the diesel generators. Given a fuel price p_{fuel}, fuel expenditures in the first year CF can be expressed as:

$$CF = p_{fuel} \cdot q_{fuel}$$

Given a capital recovery factor CRF to split a present value into annuities over the whole project lifetime (and its inverse performing the opposite), the final NPV for the whole project can then be expressed as:

$$NPV_{total} = \sum_i NPV_i + \frac{CF}{CRF}, \qquad with\ CRF = d \cdot \frac{(1+d)^T}{(1+d)^T - 1}$$

Levelised costs of electricity $LCOE$ imply an electricity price per unit, as used in ordinary electricity tariffs for instance. As such, we define them as the ratio between the annuity of total costs and the successfully supplied electricity in the first year (analogous to the supply indicators):

$$LCOE = NPV_{total} \cdot \frac{CRF}{E_{ss}\ [kWh/a]}$$

Lastly, the tool computes breakeven grid extension costs npv_{ext}. They indicate how expensive a grid extension may be, relative to a unit distance, before the off-grid approach would become superior. They are based on the breakeven grid extension distance, as defined and analysed in [39, 203ff, 40]. Importantly, this includes the assumption that the grid is able to supply all intended demand, as opposed to the off-grid system, which may not be. Therefore, at the breakeven point itself, the $LCOE$ of a grid extension are equal to or lower than those of the off-grid solution. Using a distance D to and given a fixed price for electricity p_{el} from the national grid, the breakeven grid extension costs can be calculated as NPV per km:

$$npv_{ext} = \frac{1}{D} \cdot \left(NPV_{system} - \frac{E_{dem} \cdot P_{el}}{CRF} \right)$$

2.4 System parameters

The following parameters have been chosen for the simulation (a summary is included in Appendix A.2):

Electricity distribution in the local grid is subject to 12% losses from inverters and distribution cables [41,p. 74]. The distribution grid itself is realised with a ring-shaped feeder bus and extended to the households by a meshed network of connectors. The cable lengths are estimated based on the area covered by the village and the number of households to be interconnected. For charge and discharge, the system prefers lithium-ion batteries over lead-acid batteries, as the former show a longer cycle life[42, pp. 49,52]. Discharging is assumed to be free of losses with a depth of discharge (DOD) dependent on battery type (Lithium-ion: 80 %[42, p. 52] lead-acid: 50 %[42, p. 49]). For charging, constant Ah efficiency is assumed (Lithium-ion: 95 % [42, p. 45], lead-acid: 80 % [43p. 417]). This simplification ignores the dependency of charge efficiencies of both lithium-ion and lead-acid batteries on their state of charge (SOC). Also, battery degradation is neglected. The efficiency of diesel generators is dependent on their load factor LF. The simulations assume that diesel generators run on load factor steps of 10 %, strictly rounded up to the higher share to ensure that the intended demand is supplied. This results in higher fuel consumption and more unused generation than in optimal, continuous operation. The fuel consumption q_{fuel} depends on the rated capacity P_{rated} and actual generation P [44], resulting in a maximal diesel generation efficiency of 30.7 % at full load:

$$q_{fuel} = P_{rated}(0.08415 + 0.246 \cdot LF)$$

Technical parameters for mono- and polycrystalline photovoltaic modules (mono-PV / poly-PV) were chosen based on market research. With 18.3 % (mono-PV) and 16.6 % (poly-PV), PV efficiencies are slightly higher than in literature (e.g. mono-PV: 15 %, poly-PV: 14 % [45, p. 44]). Additionally, a performance ratio PR of 90 % is considered for „[l]osses due to array mismatch, dirt, shading“ [41, p. 75]. The simulation neglects module degradation during their lifetime.

3 The case study: Bayhan A'mas Aljabal

As a case study, we analyse a large pre-electrified community in Yemen. Households own various consumption devices from earlier times when national grid supply was present. The majority of households own PV systems, but they are unable to supply their demand sufficiently. With the large pre-existing capacities, the case should provide an obvious potential for a swarm grid.

With 14 out of the 18 million Middle Easterners without electricity access, Yemen is the least electrified country in the Middle East; this amounts to approximately 48% of Yemenis, unequally distributed with 68% of the country's rural population affected [1, p. 116]. However, the actual number may be even higher, as it mostly accounts solely for interconnection with a grid and not necessarily for actual supply.

The country is marked by widespread poverty, and progress in human development has been virtually absent during the last three decades [46]. This situation has peaked in the ongoing war, leaving the vast majority of the country without any electricity from the grid. Hence, in most cases, the remaining electricity supply is limited to a few hours daily, and it depends on private diesel generators and PV panels, despite occasional scarcities in diesel and tremendous surcharges for solar equipment.

The village Bayhan A'mas Aljabal is located 45 km northeast of the Yemeni capital Sana'a, connected by unpaved roads. The village has some 1700 inhabitants with a population density of approx.. 525 people/km^2. It contains a school, two mosques, and a small health care unit. Occupation is concentrated in agriculture and some smaller private businesses. Temperatures can be high with an average of 30 ◦C during summer days (monthly day and night temperatures from [47]). Conditions are not favourable for hydro or wind plants, but solar irradiation is overly high (see Section 4, monthly cloud cover factors from [48]), as is the case for Yemen in general [49].

Data for the case study is taken from surveys of the village undertaken in 2016 by the Energy Access and Development Program (EADP). Each consumer (households, business, others) was surveyed for number and type of load devices, storage and generation capacities, and previous investments in current supply systems. An aggregated usage (turn-on) schedule for each consumption device was compiled for the whole village. Tables of input parameters can be found in Appendix A.2.

The village was connected to the national grid until 2014, with sporadic service of up to 2 hrs per day. Since the connection broke down completely, many households have invested in their own generation units. Renewable energy supply has become increasingly popular in the country [50, 51], and studies confirm the large potential of off-grid solutions [34, 35]. As PV systems have become competitive to diesel generators, primarily due to occasional fuel shortages, 85% of consumers in Bayhan have decided to invest in SHS, most of them using older car batteries for storage. Capacities accumulate to 18.5 kW_p poly-PV, 65 kW in diesel generators, and a battery capacity of 173.5 kWh lead-acid. Since the village had (sporadic) access to the national grid in previous years, its households and businesses own various devices. Households appliances include lamps, fridges, vacuum cleaners, and blenders. Businesses own various specialized devices such as water pumps, welding machines, sewing machines, and mill grinders. The health care unit owns a laboratory and an X-ray machine. Obviously, most of these devices are not used due to the shortage of electricity.

In addition to the aforesaid, the study assumes a project lifetime T of 20 years and a discount rate d of 10 %. Transport is assumed at 17.15 €/t from the Yemeni port Aden [52]. The diesel price amounts to 0.708 €/l, considering neither transport costs nor fuel shortages. Electricity from the national grid has an official price of 0.086 €/kWh [53]. Investment costs, NPV per unit over the time accounted, mass, and expected lifetime are given in Appendix A.2. It should be noted that these prices can be slightly upwards biased, as they do not consider any major bulk discounts; thus, investment costs in the MG might appear higher than usual.

4 Results

4.1 Demand profile

The tool computes the specific load profile for each consumer – and, thus, the whole village – as explained before and given the survey data. The presence of numerous devices, a result of the previous grid connection, leads to high yearly demand of approximately 565 MWh/a. Households account for the largest share in consumption with 85 % of total demand (largely due to electric lamps and fridges), followed by businesses with a share of 14.7%. The annual peak amounts to 175 kW, while daily demand peaks at a mean of 103 kW, typically at lunch and in the evening (see Figure 4). Irradiation is high with an annual amount of 2333 kWh/m^2. Daily global irradiation varies between 5.7 and 7 kWh/m^2. In combination with profiles of day and night temperatures, this results in a daily specific PV panel generation between 0.85 and 1.16 kWh/m^2, depending on the panel type (Figure 4).

4.2 Supply and performance indicators

The village's current **individual supply (IS)** proves insufficient with a meagre supply security of 12.4 % (see Figure 5 and Table 1). In terms of service quality, this translates to the inhabitants not being able to use electric appliances as planned for 86.7 % of the time.

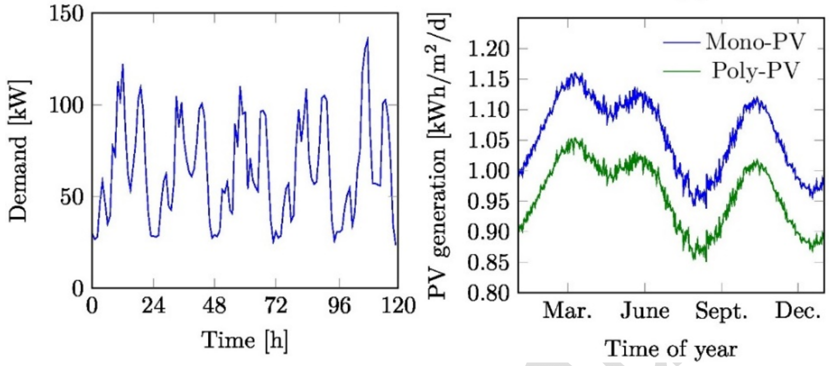

Figure 4: Overall demand (left) and specific PV generation (right) in the case study

Private households suffer most from electricity scarcity with supply security of only 10.4 % (i.e. a deficit of 2169.6 kWh/a per household). They are only provided with 0.6 kWh/day instead of 6.5 kWh/day as demanded. Businesses, in contrast, reach an average supply security of 22.2 % due to their diesel generators (i.e. a deficit of 4103.4 kWh/a per business). Yet, generator availability and size (and, thus, also supply) differ substantially between different businesses. The health care unit can supply its demand entirely, as it owns a sufficiently large generator. Total unused generation is low with 12 MWh/a, compared to the total supply deficit of 473.6 MWh/a. Batteries in the SHS are rarely used in full charge cycles: The daily mean battery charge of the village is at about 52.1 %. Thus, PV systems operate very efficiently with only a 0.7 % generation loss (0.3 MWh/a).

By interconnecting existing capacities in a **swarm grid (SG)**, a significant rise in supply security to 81.7 % can be observed (see Figure 6 and Table 2). This improvement can be largely attributed to the vast diesel generator capacities in the village that now feed-in considerably. The share of renewables in overall generation is therefore low at only 8.4 %. Fuel consumption q_{fuel} rises from 43900 l/a in the individual supply scenario to 155800 l/a.

Both households and businesses benefit from the possibility of consuming electricity from the swarm grid, as their supply security indicators rise to 81.2 % and 80.3 % respectively. On average, consumption from the grid equals 4.2 kWh/day for households and 8.9 kWh/day for businesses. Households only provide a feed-in of 0.02 kWh/day, while business feed-in 35.9 kWh/day from generators supplying on higher load factors. The health care unit has a remarkably-high feed-in of 173.8 kWh/day. Supply deficit takes place in times of peak-demand, i.e. at noon and in the evenings. Batteries are used more intensively than in IS, but they continue to have a low daily mean charge of only 55.3 %, and fewer batteries complete full charge cycles. They store the insignificant excess PV generation (0.02 kWh/day) but mostly store diesel generator overproduction, essentially eliminating generation losses.

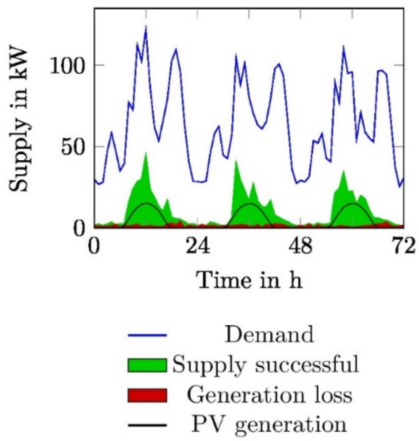

Figure 5: Supply in the Individual Supply scenario

E_{dem} [MWh/a]	565
E_{ss} [MWh/a]	91.4
E_{unm} [MWh/a]	-473.6
E_{loss} [MWh/a]	12
q_{fuel} [l/a]	43900
Renewable fraction	44 %
Supply security	12.4 %
Generation efficiency	98.5 %

Table 1: Supply in the Individual Supply scenario

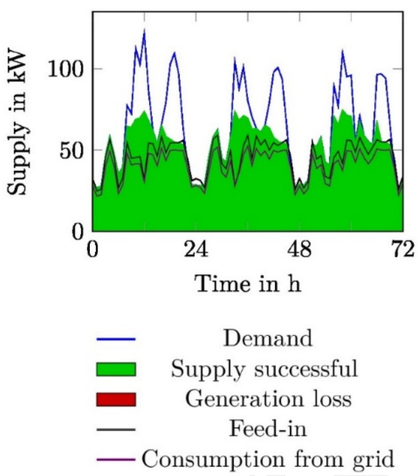

Figure 6: Supply in the Swarm **Grid scenario**

E_{dem} [MWh/a]	565
E_{ss} [MWh/a]	460.8
E_{unm} [MWh/a]	-104.2
E_{loss} [MWh/a]	0
$E_{feed-in}$ [MWh/a]	390.9
$E_{consumption}$ [MWh/a]	346.6
$E_{losses,grid}$ [MWh/a]	49.4
q_{fuel} [l/a]	155800
Renewable fraction	8.7 %
Supply security	81.7 %
Generation efficiency	100 %

Table 2: Supply in the Swarm Grid scenario

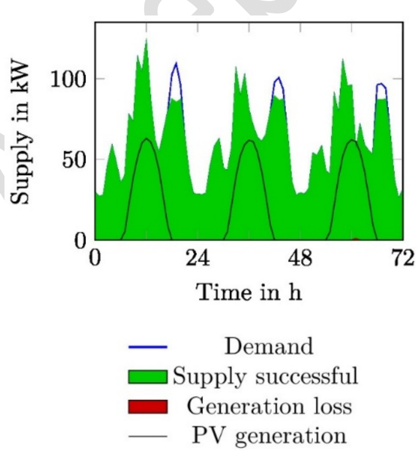

Figure 7: Supply in the Micro Grid scenario

E_{dem} [MWh/a]	565
E_{ss} [MWh/a]	551.6
E_{unm} [MWh/a]	-13.4
E_{loss} [MWh/a]	0.2
q_{fuel} [l/a]	1352003
Renewable fraction	37.8 %
Supply security	97.6 %
Generation efficiency	99.9 %

Table 3: Supply in the Micro Grid scenario

The OEM results in a cost-minimising combination of generation and storage for the micro grid (MG), including 98.5 kW diesel generator capacity, 20.8 kW_p mono-PV and 58.5 kW_p poly-PV, as well as 4.3 kWh lithium-ion and 23.7 kWh lead-acid battery storage. This system yields a supply security of 97.6 % at a share of 37.8 % renewable generation (q_{fuel}: 137700 l/a). Supply deficits occur during evening hours and amount to 13.4 MWh/a. Figure 7 and Table 3 summarise the results. Generation losses are only marginal (0.2 MWh/a).

4.3 Cost indicators

In terms of $LCOE$, IS proves to be the most expensive solution (52 €ct./kWh), followed by SG (29.4 €ct./kWh) and MG (23.1 €ct./kWh). This includes sunk costs in the form of currently-existing capacities for IS and SG scenarios. In absolute terms, it is no surprise that IS proves cheapest with an NPV of 431 t€. Yet it is noteworthy the centralised MG holds also lower total costs than SG, with $NPVs$ of 1155 t€ and 1230 t€ respectively. The subsequent section discusses the potential reasons for this result. In terms of breakeven grid extension costs, the results apply likewise: SG proves superior above 18.8 t€/km, compared to MG with only 17 t€/km.

The results are summarised in Table 4. Note that the breakeven costs for IS are not given as they lack any meaningful interpretation: Its NPV would be in balance with expenditures for electricity from the national grid, while supplying only a small share of the village's demand.

Performance indicator	Individual	Swarm Grid	Micro Grid
Supply security	12.4 %	81.7 %	97.6 %
Generation efficiency	98.5 %	100 %	99.9 %
NPV [t€]	431.1	1229.6	1155.3
$LCOE$ [€ct/kWh]	52	29.4	23.1
Breakeven grid extension costs [t€/km]	N.A.	18.8	17

Table 4: Indicators of all three scenarios compared

5 Discussion

In the case study, individual supply is confirmed to be unable to meet the village's demand, and supply improves considerably with the implementation of a swarm grid. Noticeably, though, a micro grid outperforms the swarm grid both in terms of supply and costs. The following subsections will highlight and discuss these points, alongside many issues arising from the results.

5.1 Supply and performance

Supply performance will be evaluated with the well-known multi-tier framework for electrification [54, 77f]. The consumers have an intended average demand of 6.5 kWh/d (2375.9 kWh/a). This would be classified as Tier 4 or, given the need for 24 h service and a high base load of about 22 kW, even Tier 5. Yet, the current solution of individual supply enables Tier 2 services only. Numerically, barely 0.6 kWh/day can be realized on average, and the high share of hours with supply deficits translates to sufficient electricity supply for only about 4 h/d (although shared diesel generators – not considered in the simulation – may improve this picture slightly).

The rise in supply security from 12.4 % (IS) to 81.7 % (SG) is evidence for the large benefits a swarm grid may have for pre-electrified communities. It is able to provide the village with Tier 3 electricity access at a capacity of 5.3 kWh/d and an uninterrupted supply of approximately 14 h/d. In contrast, the MG offers an electricity supply of Tier 4 with about 3 hours of generation deficit per day.

Improvements both in system modelling and additional swarm grid controller capabilities, discussed below, could improve the benefit of a swarm grid. The performance indicators imply that interconnecting groups of households to include PV systems and a diesel generator would noticeably improve their supply. Hence, this could be an immediate and cost-effective alleviation until a sufficient supply solution for the whole community arrives.

Due to the large pre-existing battery capacities, only minor PV generation losses of 0.7 % have occurred for the sole SHSs in the IS scenario. This differs crucially from other studies, which cite large losses for individually-generated PV electricity (e.g. about 30% for a case in Bangladesh [55]) as the main driver for swarm grid benefits. In this case, however, simulated SOC profiles of batteries show that full charge occurs seldom or even never, indicating oversized storage capacities.

Closely related to this, the already-large capacities of diesel generators are the primary driver for an improved supply in the swarm grid. However, this ties grid performance closely to the load factor steps of diesel generation control. If the generator were able to match demand closely with load factor steps of 1 %, the swarm grid would perform worse (supply security: 80.5 %, $LCOE$: 30.8 €ct./kWh) than in the case of rigid control with load factor steps of, for instance, 30 % (Supply security: 91.1 %, $LCOE$: 25.4 €ct./kWh). In this case, batteries are large enough to store the excess generation and use it later. Thus, surveys should include the operation conditions of diesel generators to properly forecast swarm grid potential.

A more adequate approach can be found in the micro grid, which supplies almost 100 % of the intended demand (the slightly lower result of 97.6 % does not indicate an invalid approach but room for improved power flow algorithms in the simulation and for the OEM). High supply security and generation efficiency confirm that an OEM based on a mean demand profile of 24 h is sufficient for a comparison between different scenarios, but not for system design. A rough estimation of the $LCOE$ for completely supplying demand is 22.5 €ct./kWh (margin of 0.5 €ct./kWh).

The necessity for the strategic scheduling of generation and storage processes can be observed for both MG and SG. Supply deficit peaks occur during the day (SG) and during evening hours (SG and MG) when the batteries are fully discharged. The decision to always discharge batteries prior to using diesel generators (see Figure 3) prohibits batteries from providing support in peak hours and results in empty batteries even before the evening peak. Supply security could have been increased using smarter algorithms in all scenarios. This issue is by no means limited to the simulation, but the lack of strategic scheduling affects most off-grid households and villages. Scheduling the battery discharge for evening hours should increase supply security and needs to be considered for both for simulation and swarm grid controller design.

5.2 Economic and social aspects

Judging from the $LCOE$ of the supply systems, IS is by far inferior with electricity costs of 52 €ct./kWh. Implementing a swarm grid would be able to decrease these costs to 29.4 €ct./kWh, and a micro grid appears as the least-cost option with 23.1 €ct./kWh. The breakeven grid extension costs of MG are 17 t€/km and 18.8 t€/km for SG. As such, both SG and MG could be about as expensive as a common grid extension with costs between 6 t€/km and 22 t€/km, depending on remoteness and territory [42, p. 5].

In the specific case of Bayhan A'mas Aljabal, a grid extension is not an alternative even if it were cheaper than the off-grid solutions. Conflict in Yemen has taken its toll on grid infrastructure and continued damage to newly-built infrastructure cannot be ruled out. Moreover, as the national grid is chronically-low on generation capacities, an interconnection would not ensure sufficient electricity supply.

As mentioned previously, micro grid approaches often ignore pre-existing supply units. This process results in asset stranding and may have a detrimental effect on villagers' incentive to participate. Yet, the inclusion of previous sunk costs increases the $LCOE$ only slightly by some 4 %. Other approaches, such as a micro grid that includes previously-installed capacities by purchasing them from the owners, is possible but not considered in this study.

A swarm grid, on the other hand, builds upon already-existing capacities. In its $LCOE$ of 29.4 €ct./kWh, previous investments in currently-existing capacities are included (SHS: 28.7 t€, estimation for diesel generators: 22.6 t€). However, in line with the MG estimation, exclusion only yields a moderate reduction in $LCOE$ of 4 %.

Nevertheless, and not only to compare costs, it is essential to differentiate on a case-by-case basis how these previously-installed capacities will be treated. Naturally, for a narrower gap between micro and swarm grid, this accounting issue could conceal an eventual switch in the least-cost option, such that the wrong system design will be preferred. However, as elaborated above, this question has also profound social implications. As off-grid work is linked to bottom-up action, compliance with the project is essential, but residents owning capacities before the project may become reluctant or even oppose it if their assets are in danger of being rendered stranded. Also, setting electricity tariffs – an issue this article does not consider -, inevitably becomes more complicated.

Although the micro grid is less expensive than the swarm grid, the possibility of implementing a swarm grid in a staggered fashion can be pivotal. The central nature of the micro grid will require the system to be built in a single project, implying all non-operational costs are due upfront. In the context of a conflict-torn developing country with a dried-up public budget, such as Yemen, government financing is unlikely, and competition for international grants is high. Self-financing would require a high degree of coordination, not to mention the infeasible costs. Hence, the step-wise and modular nature of swarm electrification enables neighbouring consumers to form smaller groups and invest quite small amounts in an interconnection. Over time, such different networks can be interlinked again. As elaborated above, given the "right" subset of households, even such smaller interconnections can have a robust positive impact: If the interconnected groups contain both solar systems and fossil fuel generators, the supply can be improved significantly.

At this point, it should be mentioned that cost indicators in our study are rather high, but still in line with the literature and correct, given the simulation's input parameters. Even an unlikely upward bias of prices would not affect our conclusions regarding the comparison of micro and swarm grid, since their comparison is made on a relative basis. Also, the rather high figures indicate the benefits of public action in the electricity sector as opposed to the current trend of regarding individual action to be the new benchmark.

Nevertheless, it is crucial to analyse why micro and swarm grids yield different costs. A first look at the composition of investment costs (see Figure 8) reveals large similarities. As the grid topology is identical, distribution grid costs are equal with 59.7 t€. Costs for the central micro grid controller (in MG) amount to 85.7 t€, while controllers and inverters in the SG amount to 20 t€. A brief sensitivity analysis shows that $LCOE$ for the swarm grid are linearly-dependent on the expenses for the swarm grid controller. With controller costs composing only a small share of the overall costs, $LCOE$ with controller costs of 30 € decrease just slightly to 29,12 €ct./kWh, while they would increase to 29,7 €ct./kWh for controller costs of 100 €.

Diesel generators account for a minor part of the investment (SG: 31.3 t€, MG: 46.8 t€), while fuel costs are the primary cost component (MG: 868.9 t€ / 75.2% NPV, SG: 1001.1€ / 81.4% NPV). The MG has higher diesel generator and PV capacities, resulting not only in better supply security but a higher renewable factor for the MG, which decreases fuel expenditures and, thus, $LCOE$.

While optimal investment in PV panels is quite high in the MG (45.5 t€, 79.5 kW_p), the existing panels in SG only amount to an investment of 10.9 t€ (18.9 kW_p). At the same time, expenditure for battery capacities equal 17 t€ (MG, 28.8 kWh) and is significantly lower than for the SG with 106.4 t€ (173.2 kWh). A minor share (16.7%) are previous investments, whereas the rest will be future reinvestments to replacement the current capacities.

Despite the oversizing of batteries, the SG assumes an entire replacement. If capacities were only replaced to the optimal PV-to-storage ratio as suggested by the OEM, only 16.9% of present storage costs would have to be invested. This would result in decreased $LCOE$ of 27.3 €ct./kWh, saving a margin of 2.1 €ct./kWh. Moreover, additional PV capacities in the SG (in combination with appropriate storage capacities) could increase successfully supplied demand at even lower $LCOE$ by decreasing fuel expenditures. Thus, we strongly advise profit and non-profit actors to not only provide SG control units to a project site but also consulting for future investments, e.g. by implementing an algorithm for automated advice on SG development in the SG controller.

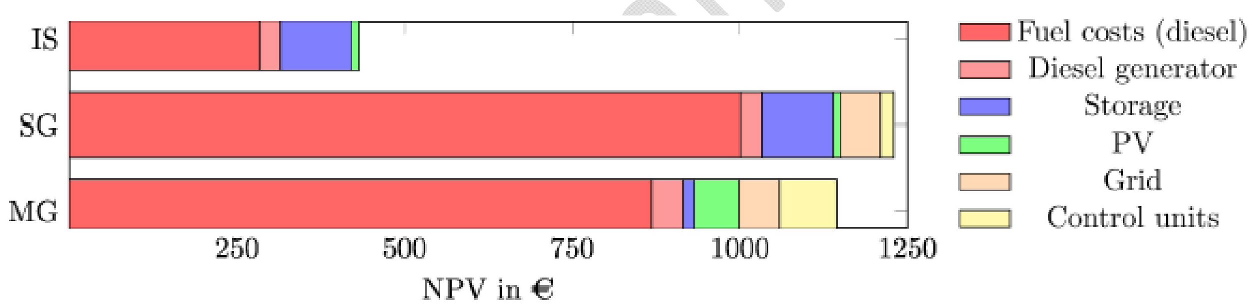

Figure 8: Composition of the NPVs for all scenarios

The influential role of fossil fuel generation in our case is subject to social and economic remarks. Rural electrification is often set in the context of sustainable development, a term not equal to but often used in close connection with green energy. However, depending on generator and fuel costs, a swarm grid could create incentives to invest in fossil fuel generators to benefit from their feed-in. This may not only be unwanted from an environmental perspective, but fuel expenditure indicates that higher renewable factors might decrease $LCOE$. Whether such incentives are set is largely contingent on government policies with regard to subsidisation and taxation of fuel and PV systems. Nevertheless, a promising business model for fossil fuel producers in swarm grids might attract the necessary funding to invest in extensions and enhancements. Thus, drawing a clear conclusion is difficult.

6 Conclusion

Throughout the rural Global South, individual systems for electricity supply are popular, yet mostly unable to meet the intended demand of households. Swarm grids represent a possible solution to improve pre-electrified communities towards better energy services: Existing generation and storage can be interconnected in a decentralised local power distribution grid. This article used a simulation approach to compare individual supply, swarm grid, and a micro grid for the case of a large, pre-electrified community in rural Yemen. The different cases have been compared by means of their service quality and financial indicators.

The study has been able to confirm the low quality of individual supply: Only a tenth of the intended demand could be supplied, resulting in a Tier 2 electrification level, and levelised costs were the highest among all systems. We confirmed that a swarm grid has the potential to noticeably improve supply, resulting in a Tier 3 electrification with more than 80 % of demand realised at nearly half the levelised costs. Yet, a centralised micro grid was shown to outperform the swarm grid for both costs and supply, leading to a Tier 4 electrification.

A major part of the results originate in the case study's specific parameters, i.e. the large amount of pre-existing diesel generators and oversized storage. They are the main driver for the significant benefits of a swarm grid, as existing generators could be run on higher load factors and their supply could be distributed towards smaller customers in a swarm grid who were undersupplied in autarky. PV systems, on the other hand, do not substantially contribute to this effect, as their losses were low due to oversized initial battery capacities. This is opposed to other studies, which cite large PV generation losses in individual supply as the main driver for swarm grid benefits. As a consequence of the high fuel expenses and misguided reinvestments in oversized battery capacities, the micro grid has proven superior and less expensive due to its approach of installing the optimal energy mix.

Certainly, the idiosyncrasy of the case study reduces the possibility of generalising the results. Yet, this situation may well affect a significant amount of communities throughout the Middle East, and also worldwide. Many of them are not pre-electrified by means of professional planning but in an uncontrolled and individual way that could lead to mis-sized capacities for all components. A future mapping and analysis of off-grid investment behaviour in the Middle East will be crucial to making more profound statements about the sector (and adequate policies), but, in the absence of a scientific study, survey data by the Energy Access and Development Program for other communities hints at a similar pattern. In the case analysed, the swarm grid's benefits arise mostly from distributing fuel-based generation, leading to a series of economic and social considerations. Firstly, the resulting profit margins may create incentives to increase fuel generators capacity, which is at odds with many rural electrification projects attempting to support renewable energy systems. Of course, this depends on the relative price of fuel generation and PV systems, which is mostly an outcome of domestic tax and subsidy schemes. Secondly, the process would effectively turn some villagers into producers of electricity, while most others remained consumers for the most. Although most (especially low-income) households may not disapprove of remaining pure consumers, this uneven development is strongly opposed to the concept of prosumerism and the benefits advocates ascribe to it.

As a corollary, the tremendous difference between the micro grid's optimal energy mix and the swarm grid shows that the individual decisions regarding the purchase of whatever generation and storage capacities are far from optimal, at least regarding the joint community. Therefore, even a swarm grid may attempt to shift the trajectory towards the optimal energy mix by not replacing existing capacities but instead adding optimal capacities, when lifetimes are reached. This, however, would be another step towards guided or aided infrastructure planning and contribute to the demise of the bottom-up concept. Still, to sustain the grid's financial efficiency, the importance of at least partially including experts in grid planning and reinvestment decisions can be highlighted. We also derive this conclusion because the study has proven the potential for the non-trivial strategic scheduling of generation and storage. Lastly, a swarm grid will require at least some form of central planning to develop tariffs and billing systems for the local trade of electricity. Thus, the degree to which swarm grids are decentral beyond their physical topology is questionable.

Finally, it is worth emphasising that this study is a macroscopic simulation of the proposed AC swarm grid. Hence, while making an essential advancement regarding the comparative assessment of off-grid solutions and the design of an AC swarm grid, crucial details regarding electrical control design are left for future research and development. This applies in particular to the non-trivial design of inverters, which are required to run in parallel, and the communication infrastructure within the grid. Although we assume that adding the layers of control and communication design will neither change the approach's feasibility nor its merits, current research cannot provide certain evidence. However, and despite the above, swarm grids can be a viable plan, even in communities like the one analysed. In accordance with the economic concept of second-best solutions, a micro grid may be superior but infeasible, as the largest portion of cost is upfront investment. Given the scarce capital of low-income households and responsible governments, the interconnection of a small group of households can already lead to significant improvements in the quality of supply at relatively low cost, if the households complement each other in generation devices or demand patterns. Then, and in line with the evolutionary concept of swarm grids, different grid stages can form a bridge between individual supply and the establishment of a stable grid infrastructure with sufficient supply.

Appendix

A.1 Optimal energy mix

A micro grid is often planned centrally by a team of experts. Decision-making tools, such as numerical programming or gird design software, help to derive an optional energy mix (OEM), i.e. the cost-minimising set of generation and storage capacities that ensures a successful supply of the demand at all times. For our micro grid case, we assume such optimisation is done in advance and provides the basis for grid design. Hence, before simulating the electricity flows, the tool runs a program to find the least-cost combination of capacities CAP for diesel generator, monocrystallin and polycrystallin PV panels, as well as lithium-ion and lead-acid batteries. The optimisation program uses the Python 3 module scipy.minimize.optimize (SLSQP-Method) and the technical parameters and costs specified for the simulation analysis. The objective is to minimise the levelised costs of electricity as given by the equations below, based on a time series of 24 h for both irradiation and overall demand (as the mean of yearly data), including losses. Inverter costs do not have to be considered, as they are included in the micro grid central controller (MGCC), which is determined by the maximum load. Generation control of the diesel generator is possible without fixed load factor steps LF

$$min\{LCOE\}$$

$$LCOE = \frac{NPV_{system}}{\sum E_{dem,oem} \cdot 365 \cdot a} \geq 0$$

$$P_{gen,pv} = P_{irrad} \cdot \frac{CAP_{pv}}{P_{irrad,test}} \cdot PR$$

$$P_{gen,diesel} = LF_t \cdot CAP_{diesel}$$

$$NPV_{diesel} = CAP_{diesel} \cdot npv_{diesel}$$

$$C_{var,diesel} = p_{diesel} \cdot \sum_t q_{fuel,t,oem} \cdot 365 \cdot a$$

$$NPV_{battery} = \sum CAP_{battery,i} \cdot npv_{battery,i}$$

$$0 \leq LF_t \leq 1$$

$$0 \leq CAP_{battery}, CAP_{pv}, CAP_{diesel}$$

$$SOC_{i,t+1} = SOC_{i,t} - \frac{E_{charge} \cdot \eta_{charg}}{CAP_{battery}}$$

$$LF_t = \frac{P_{dem} - P_{gen,pv} - P_{charge} - P_{gen,diesel}}{CAP_{diesel}}$$

$$P_{supply} = P_{gen,pv} + P_{charge} + P_{gen,diesel} - P_{dem} \geq 0$$

$$q_{fuel,t,oem} = 0.246 \cdot LF_t \cdot CAP_{diesel} + 0.08415 \cdot CAP_{diesel}$$

$$NPV_{pv} = \sum CAP_{pv,i} \cdot npv_{pv,i}$$

$$NPV_{system} = NPV_{diesel} + NPV_{pv} + NPV_{battery} + C_{var,diesel}$$

$$1 - DOD_i \leq SOC_{i,t} \leq 1$$

Resulting capacities of the OEM are rounded to the next highest value of available batch size (Diesel: 2.5 kW, PV: 100 W_p, Batteries: 1.2 kWh). To avoid low load shares and to maximise generation efficiency, a number of diesel generators in batch size are used in the micro grid to provide electricity.

A.2 Simulation input parameters

Evaluated interval	8760 h	
Grid efficiency η_{grid}	88 % [32, p. 75]	
Diesel generators fuel consumption	$P_{rated} \cdot (0.08415 + 0.246 \cdot LF)$ [44]	
Generation control	10 %-steps of maximal load	
Batteries	Lithium-ion	Lead-acid
Depth of discharge	80 % [42, p. 52]	50 % [42, p. 49]
Charge efficiency	95 % [42, p. 45]	80 % [43, p. 417]
Initial charge in simulation	60 % (IS, MG, SG)	
Max. charge	95 % (IS, MG), 90 % (SG)	
Degeneration	none	
PV panels	Mono-crystallin	Poly-crystallin
Efficiency	18.3 %	16.6 %
Temperature coefficient	-0.4 %/K	-0.43 %/K
Performance ratio	90 % [32, p. 75]	
Test conditions	1000 $\frac{W}{m^2}$, 25 °C	
Degeneration	none	

Table 5: Simulation parameters

Households	171
Other consumers	26
PV (poly-crystallin)	18.5 kW_p
Diesel	65 kW
Storage (lead-acid)	173.5 kWh
Previous investments (SHS)	28692 €

Table 6: Accumulated survey data for Bayhan A'mas Aljabal

Non-electrified	28
PV system	161
Diesel	1
PV system & diesel	7
Battery owners	166

Table 7: Generation groups in Bayhan A'mas Aljabal

Project lifetime	20 a
Discount rate	10 %
Exchange rates	1€ =296.769 YER 1€ = 1.18614 $
Diesel price	0.708 $\frac{€}{l}$
Electricity price national grid	0.086 $\frac{€}{kWh}$ [53]
Distance to national grid	42 km
Transport costs	17.15 $€/t$ based on [52]

Table 8: Financial parameters for the case study

Device	Units	Load W/unit
Lamps	2310	30
Iron	49	1000
TV	196	100
El. water heater	98	1200
El. water pump	39	400
Washing machine	147	400
Computer	12	250
Vacuum	30	1000
Blender	70	300
Oven	49	1000
Fridges	158	70

Table 9: Electrical devices owned by case study households

	Units	Load W/unit
Welding machine	8	10000
Sewing machine	15	2000
El. mill grinder	8	15000
Submersible pump	3	20000
Air pump	1	5000

Table 10: Electrical devices owned by case study businesses

Device	Units	Load W/unit
Washing machine	1	400
Laboratory	1	5000
X-ray machine	1	5000

Table 11: Electrical devices owned by the case study medical point

Component	Unit u	Cost [€/u]	Weight [kg/u]	Life span [a]	NPV [€/u] ⋆
LV cables					
Three phase, Cu, ø 70 mm^2 ⋆⋆	km	25630	2950	25 [56, p. 41]	25680.5
One phase, Cu, ø 4 mm^2	km	650.2	97.7	25 [56, p. 41]	651.9
MGCC⋆⋆⋆	kW_{dem}	532.04	7.124	15	617.1
Swarm controller⋆⋆⋆⋆	piece	50	0.5	15	58
Inverter (only SG)	kW	205.52	4.81	15 [32, p. 219]	238.4
Battery					
Lead-acid	kWh	195.6	24.9	3 [57, p. 11, 58]	708.2
Lithium-ion	kWh	1112.5	12.4	6 (est.,[32])	2295.5
PV					
Mono-crystallin	kWp	992.1	68.2	20 [32, p. 255, 58]	993.3
Poly-crystallin	kWp	774.4	115.1	20 [32, p. 255, 58]	776.4
Diesel generator	kW	337.2	26.2	10 [56, p. 52, 59]	467.8

Table 12: Costs of system components and weight per unit based on a market study

⋆) Including transport costs
⋆⋆) Very high costs compared to other sources but no negative effect on comparability, as SG and MG are based on the same grid topology
⋆⋆⋆) Hybrid inverter with charge controller, sized after maximal load
⋆⋆⋆⋆) Swarm grid controller including communication and charge controller for each household. Price estimated from 30 US$ for a DC SG controller [60]. Additional investment in inverter capacity for PV systems and batteries needed

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