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Article

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Research paper

Sustainable trade-off between reliability and electricity prices for geographically isolated communities

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ABSTRACT

Rural electrification has been identified as one of the essential prerequisite for the development of modern society. Provision of uninterrupted supply for rural enterprises and affordable electricity for low-income users is imperative for the revitalisation of rural areas. Stand-alone microgrids powered by renewables are currently deployed with a trade-off between cost and reliability. No user receives complete satisfaction which increases the risk of project failure over time. A more sustainable approach is presented in this paper. Users are offered a choice between 1) an electrical supply at a low price but that may be affected by low Renewable Energy (RE) availability due to unusual weather variations, and 2) a higher reliability of supply, much less dependent on weather variations, but at a higher price. The benefits and applicability of this approach have been evaluated through microgrid design simulations performed with HOMER Pro. The results show that this method gives significant benefits: 1) rural enterprises can avail reliable supply and 2) low-income households benefit from lowest electricity bills. Future work is to quantify the gain in term of social welfare for the community and to extend this concept to whole cities powered in majority by RE.

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1. Introduction

“Affordable, reliable, sustainable and modern energy for all by 2030” is a goal set by United Nations (United Nations, 2017). With one-in-eight of the world’s population having no access to electricity (IEA, 2018) this means that each year 87 million people have to be provided with an electrical access. 80% of those people are situated in rural areas (REN21, 2016) and off-grid electrification is often the most realistic solution (Oyuke et al., 2016).

If some off-grid electrification projects are successful (Ahlborg and Sjöstedt, 2015; Sovacool, 2013), field reports reveal that many others end-up being a business failure (Palit and Sarangi, 2014; Sovacool, 2013). Limited access to capital slows down the achievement of universal electrification goal (Vanadzina et al., 2019), and it is essential that the projects deployed are successful.

Abbreviations: PES, Percentage of Energy Shortage relative to the energy demand. Energy shortage occurs when energy storage is empty and renewable energy generation falls short of energy demand; LCOE, Levelised Cost of Electricity; RE, Renewable Energy

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At present, all users connected to a rural microgrid receive electricity at the same level reliability. The wide difference in user’s ability to pay for reliability and in their expectation regarding the availability of electric power is a source of discontent and a known cause of project failure (Chaurey and Kandpal, 2010; United Nations Foundation, 2014).

Affordability is critical because when some users are unable to pay their bills, the microgrid’s revenue decreases. This in turn, leads to decreased maintenance, which affect the quality and reliability of electrical supply for all users. Customers with more income, in particular users such as entrepreneurs who demand a reliable supply, may either stop paying their bills or invest in individual energy systems (United Nations Foundation, 2014) (see Fig. 1). Thus availability of electrical supply is a critical parameter. The willingness to pay for reliability depends on user’s level of affordability (Abdullah and Mariel, 2010; Hensher et al., 2014; Twerefou, 2014), and there are wide differences in household’s ability to pay in rural areas (Government of India, 2011).

This research is focused on furnishing augmented on-demand access to consumers of electricity, in remote outlying regions. The proposed solution is to offer users a choice of Quality of Service (QoS) and price through a choice of PES constraints. To this end, the Percentage of Energy Shortage (PES) was introduced as a critical design parameter for stand-alone microgrids powered

by renewables (see Section 2.1). Although the cited examples primarily refer to India, the proposed remedies are conceived to be universally applicable.

2. Methodology and simulation design

2.1. Percentage of Energy Shortage (PES): a meaningful indicator of Quality of Service (QoS)

It is a pricey proposition to design a RE microgrid that always meets the total electricity demand of a village (Daneshi and Khorashadi-Zadeh, 2012). The reliability of supply has recently been introduced as a constraint (Borujeni et al., 2017), or as a parameter in the design process of microgrids (Mandelli et al., 2016). However, in stand-alone microgrids, reliability is vulnerable to a shortage of RE generation. With advanced notification of a pending lack of RE generation, users can limit their consumption to avoid a power outage. In such off-grid cases, it seems more appropriate to use the Percentage of Energy Shortage (PES) relative to the demand, to assess the availability of supply. In the proffered method, PES is a design parameter affecting the Quality of Service (QoS) provided to consumers. The PES is defined as the ratio between “energy undelivered” and “energy demand” (see Eq. (1)).

$$\text{Percentage of Energy Shortage} = 100 \frac{\text{Energy undelivered}}{\text{Energy demand}} \quad (1)$$

2.2. Choice of PES-constraint for field applications

The “maximum PES allowed” by users influences the design of a microgrid and thus the “cost of electricity”. The relation between “PES” and “LCOE” can be found by simulations (see Section 2.4.4), and microgrid users can choose their preferred option. It is proposed here, to offer users a choice of daily energy allowance associated with few PES constraints options. This type of offer provides the necessary information for the design of the lowest cost microgrid that satisfies users’ requirement. However, for the implementation on the field, “daily energy allowance” must be translated into an “allowed functioning time” for different appliances, depending on their power ratings. To that end, an intelligent approach in the form of a game involving rural users has already been proposed (Abdullah and Kennedy, 2015). The PES constraints must also be explained in simple terms to the population, with expected variation throughout the year, depending on seasonal changes. These changes cannot be totally predicted, but simulations based on weather patterns provide estimates of the distribution of energy shortage throughout the year (Robert and Gopalan, 2018a).

When all users have chosen the energy package that suits them best, the microgrid can be designed to meet the total electricity demand with the corresponding overall PES constraint (see Fig. 2). Once the microgrid is in operation, energy shortages that occur can be dispatched according to users’ options.

2.3. Additional requirements for successful implementation of multi-PES microgrids

The practical implementation of the proposed system requires a suitable architecture (Srinivasan et al., 2013). A smart metre costing less than ten euros sends warning signals (possibly via power line communication on 175 Hz), connects and disconnects users. It communicates with a central controller which manages the real-time balance of the microgrid while keeping track of the history of power consumption for each type of user. No additional cost is expected for the control hardware, except for the cost of development. The control system uses the principle of

a standard load shedding scheme with predefined and monitored levels of energy shortage for each type of user. The monitored power interruption data can be converted into energy shortage data through multiplication by a coefficient corresponding to the average consumption of the user during this time of day (e.g. a 1 h power interruption at 8 p.m. must be multiplied by the average consumption at this time which corresponds to a higher amount of energy shortage than a 1 h power interruption at 3 a.m.). Without any weather forecast, energy shortages can be anticipated by monitoring the amount of energy stored in the batteries, while taking into consideration the time of day (e.g. a battery is not expected to be full at 8 a.m., but if it is already half empty at 7 p.m., some users may have to be disconnected to ensure that highly reliable users have enough energy throughout the night and till the next morning). A very simple algorithm is illustrated in Table 1.

The different levels X, Y and Z should be dynamically adjusted throughout the month, in order to obtain the required reliability level expected by each type of user.

2.4. Warning messages ensure that users are aware of the expected amount of energy shortage (or excess) in the day and can take proactive actions to adjust their consumption. The algorithm can be improved with a RE forecast, Barbato et al. (2014), cooperative demand response mechanisms (Rahbari-Asr et al., 2014; Rahmani et al., 2017; Robert et al., 2018) and can be optimised over multi-time steps (Hug et al., 2015). Relation between cost of electricity and PES in a microgrid.

2.4.1. Why choosing PES?

RE production is uncertain and loads vary continuously. Two aspects are considered to meet the demand at all times: storage capacity and variability of RE generation between days and between seasons. Sufficient storage capacity ensures a reliable supply despite a mismatch between electricity generation and load-demand on a particular day. Adequate generation capacity ensures sufficient energy harvesting during the season with the lowest amount of resources. Thus energy shortage depends both on energy storage and RE generation capacity.

The relation between microgrid design and the maximum PES allowed has not been well studied in the published literature. Nevertheless, a few studies (Daneshi and Khorashadi-Zadeh, 2012) suggest that design of a RE microgrid that meet 100% of the electricity demand, with no energy shortage, is a high-priced option. Determination of the relationship between PES and microgrid design requires a precise evaluation of the RE resource, the resultant electricity generated, energy storage capacity, and the load profile. This problem involves close to hundred parameters for modelling RE resource, power generation equipment, energy storage behaviour, loads and their variations, losses, financial variables and other project parameters. This justifies the use of a professional simulation software.

2.4.2. Assumptions

The cost of distribution grid depends on local specificities and do not depend on the type of user; it can be of approximately €150 per connection in India (United Nations Foundation, 2014). In this work, distribution grid costs, the cost of control system, losses and fixed costs such as metre and payment collection costs are accounted as a generic 10% additional cost over the LCOE calculated by the software. That is, the price of electricity is assumed to be equal to the Levelised Cost of Electricity (LCOE) plus 10%. This is simplified and conservative assumption was made to focus on the demonstration of the novel idea. Similarly, to reduce general explanations, the discount rate was assumed

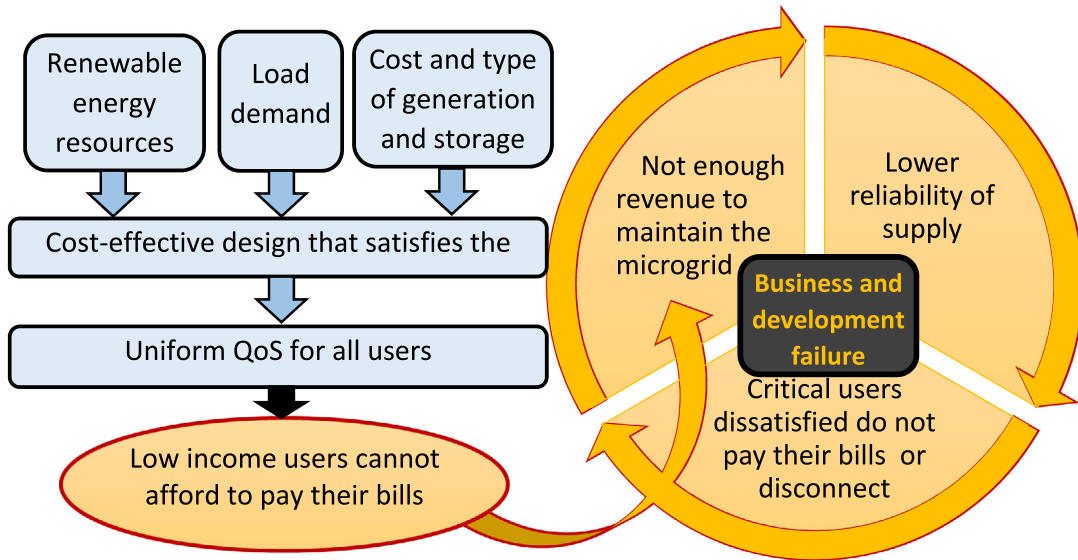


Fig. 1. Design of microgrid and causes leading to microgrid business failure.

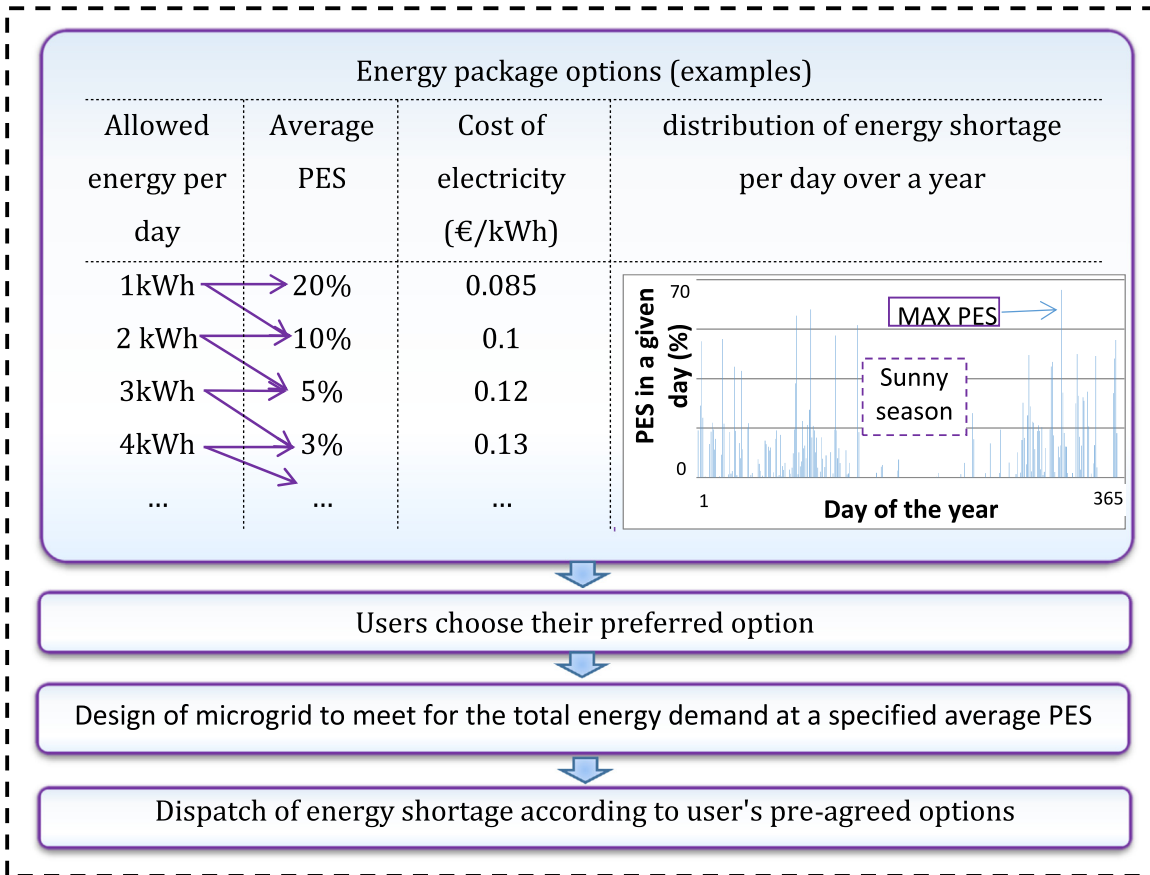


Fig. 2. Choice of energy package by users and corresponding microgrid design and operation.

Table 1

Proposition of architecture for an algorithm managing the microgrid energy balance and the reliability of users.

	Thresholds (different for each hour of the day)	Types of user connected	Types of user disconnected
State of charge of battery bank (SOC) (%)	Above Z (e.g. 70% at 7 p.m.; 50% at 9 p.m...) Between Y and Z (e.g. between 50% and 70% at 7 p.m.) Less than X (e.g. 50% at 7 p.m.)	Type 1, Type 2 and Type 3 Type 2 and Type 3 Type 3	- Type 1 Type 1 and Type 2

to be null in all simulations, though further information on its impact on simulation results can be found in Robert et al. (2018).

To isolate the impact of PES on microgrid design, it was assumed that all users have the same load pattern.

The technical rate of failure of the microgrid components was not taken into consideration. It is however possible to include it in the evaluation of the global reliability of electrical supply (Moradi and Khandani, 2014).

Euro, US dollar and Indian Rupee rates of exchange were taken as of 17.07.2017: 1.00 EUR = 75.01 INR = 1.15 USD Source: www.xe.com.

2.4.3. Financial parameters and Levelised Cost Of Electricity (LCOE)

The Net Present Cost represents the total cost that the system incurs over its lifetime minus the salvage value of all equipment (see Eq. (2)). The lifetime of a project is a time period used to compare the economics of different designs. It can be the expected service life of the most important generating equipment, but not necessarily (e.g. 20–30 years for solar panels). The salvage value of equipment represents the remaining value of equipment at the end of the project lifetime. It is calculated proportionally to the percentage of the service time that remains at the end of the project lifetime. This indicator enables researchers to compare the cost of projects using equipment of different service times. The NPC is calculated by summing the total cash flows in each year over the project lifetime (see Eq. (2)).

$$NPC = \text{Capital cost} + \text{M\&O cost} - \text{salvage values} \quad (2)$$

The Levelised Cost Of Electricity (LCOE) is the most widely used indicator to represent the cost of electricity for RE projects. It takes into consideration: investments, maintenance and operations cost, discount rate and inflation rate. Assuming that the discount rate and inflation rates are null, the LCOE can be calculated by dividing the total cost of the system by the total electricity consumed (see Eq. (3)).

$$\begin{aligned} LCOE &= \frac{\text{Total costs}}{\text{Electricity consumed}} \\ &= \frac{NPC}{(\text{Electricity generated} - \text{Electricity lost})} \end{aligned} \quad (3)$$

In a stand-alone microgrid, the LCOE corresponds to the minimal price at which electricity should be sold for utility to break even. It is used here, to compare the different designs among each other: each microgrid design was associated with the LCOE value corresponding to it.

2.4.4. Simulation process

HOMER Pro software (Version 3.12) was chosen for this simulation because of its wide acceptance in both industry and academia (Farret and Simoes, 2005; Sinha and Chandel, 2014). The software receives all projects inputs about loads, available resources, and cost and technical characteristics of different equipment. Once all parameters are set, the researcher enters a range of possible designs to be simulated, for example 0 to 10 kW solar panels, 10 to 15 batteries of 1 kWh, etc... The software can use time steps from 1 hour to 1 min. For each time step, RE generation is calculated based on the amount of RE available and the power curve of the generator.

HOMER Pro allocates energy to the load or stores the excess production in battery storage. When energy storage is full, the excess production is lost. If the production and storage are insufficient, part of the load cannot be supplied, which is accounted as energy shortage. Designs are then ranked according to the least cost criteria. The cost of electricity is calculated from the total project cost for each design (see Section 2.4.3). The relation between “PES constraint” and “cost of electricity” can then be established with successive determination of the least cost design associated with different constraints of PES. (see Fig. 3).

Table 2

Capital and maintenance (O&M) cost for stand-alone solar photovoltaic projects.

	Capital cost	O&M
Solar panels and inverter	€ 960/kWp	€ 10/kWp/a
Lead–acid batteries	€ 75/kWh	€ 1.5/kWh/a

3. Test scenario

This section presents a realistic application of the proposed methodology. An Indian village of 100 families was assumed to be powered by a stand-alone, solar microgrid. Users have been classified under three types depending on their budget. If the Percentage of Energy Shortage (PES) is assimilated to an equivalent percentage of time of power interruption, the maximal PES that is acceptable for most people in India is 40% (World Bank, 2015). The most economical microgrid designs were found for a range of PES constraints from 0.1% up to 50%. The correlation between PES and LCOE was established with the method illustrated in Fig. 3. PES constraints were then assigned to each user type depending on their income level. Finally the least cost design able to satisfy all PES constraints was generated.

3.1. Weather data

The solar electricity generation of the 31.5 kWh installation on the Amritapuri campus of Amrita University was collected every 15min for a year. These data were used as inputs for the design solar microgrids by scaling them up or down, thus assuming more or less solar panels. The average Global Horizontal Irradiance (GHI) of the site was 4.98 kWh/m²/d according to the National Renewable Energy Laboratory data base.

3.2. Cost of equipment and financial parameters

The costs for solar equipment and batteries were taken as per the official benchmark cost for 2017–18 from government of India, Ministry of New and Renewable Energy (2017), (see Table 2).

The solar panels installed in Amrita University have an efficiency of 18.5%. The nominal operating temperature of the solar cell is 47 °C and their temperature coefficient is –0.391. Standard Lead–acid battery storage was used for the simulation, which is common in rural microgrids. The Lead–acid battery selected had 1 kWh capacity, a round trip efficiency of 80% and a lifetime of 10 years or a maximum energy throughput of 800 kWh (the standard assumption in HOMER Pro). The maximum depth of discharge was set at 40%. The capacity reduces as the rate of discharge increases as per the in-built model for Lead–acid batteries from the software. The inverter and rectifier costs were included in the solar costs, their efficiencies were both set at 95%.

3.3. Description of users

3.3.1. Average consumption, budget, types of user and load profile

The average consumption per household is 54 kWh/month in rural India (World Bank, 2015) and 45 kWh/month in Kenya (Abdullah and Mariel, 2010). The monthly electricity consumption is expected to be less in a newly electrified village; it was assumed to be 41 kWh per month (or 1.36 kWh/d) for the test scenario. The willingness to pay for electricity service was limited to 5% of household budget (World Bank, 2015). Three different trustworthy references disagree on the average income per month, per rural household in India, which was reported to be €185 (Rs. 14000) in People Research on India's Consumer Economy (2014), €107 (Rs. 8000) in Singh (2014), and €90 (Rs. 6750)

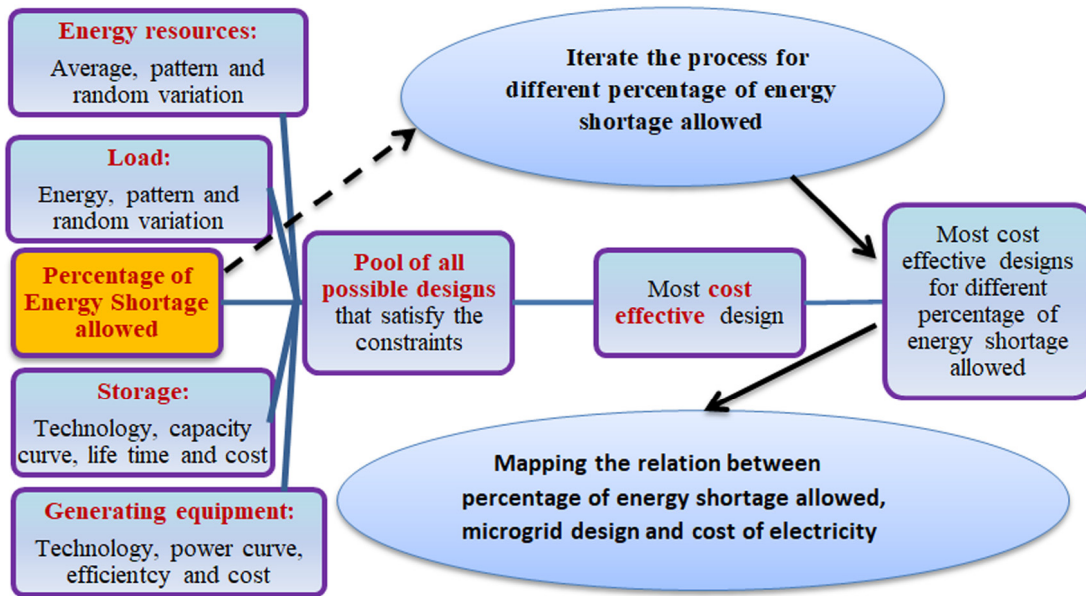


Fig. 3. Methodology to establish the impact of “allowed PES” among other parameters, on microgrid design and on total cost.

Gill et al. (2017). The average household budget was assumed to be €117 (Rs. 8800) per month. For simplicity, rural users have been classified into three types.

- Type 1 users are assumed to have only basic needs such as lighting loads, a phone charger and in some cases a fan or a radio.
- Type 2 users are assumed to have an additional TV, more lighting loads, and in some case a small manufacturing unit such as a sewing machine or handicraft tools.
- Type 3 users represent users such as critical public loads, telecom towers, rural hospitals, and potentially richer households who demand a highly reliable supply.

The distribution of users among the three types may vary greatly from village to village. It depends on the distribution of revenue (World Bank, 2015) but also on the number of small manufacturing units and critical loads (Robert et al., 2017). Based on Rawal and Swaminathan (2011) and Shukla (2010), the overall distribution was assumed to be 35% of Type 1 users, 50% of Type 2 users and 15% of Type 3 users (see Table 3).

Various community load profiles are proposed in the energy literature (European Commission, 2008; Fall et al., 2007; Martensen et al., 2012). These data were used and complemented by field experience of rural electrification to define a load pattern for the village that was simulated. The load profile used is presented in Fig. 4. Since electricity is mostly consumed by households, the greater part of consumption occurs early morning and early at night. A daily random variation following a Normal distribution with a standard variation equal to 10% of the average consumption was assumed around this profile. The monthly average temperature in the selected location varies only from 25.4 °C to 27.3 °C (source: NASA surface meteorology data base), therefore seasonal variation was not considered in the simulation.

4. Results

4.1. Optimal microgrid design

The solar production data were scaled up or down by the software to estimate the number of solar panels required. The designs that met the demand at the lowest cost for different PES

Table 3
Distribution of users and their consumption in the test village.

	Type 1 user	Type 2 user	Type 3 user	*Total **Average
Number of users	35	50	15	100*
Monthly budget per user (€)	50	110	300	117.5**
Consumption per user (kWh/d)	0.75	1.3	3	1.36**
Cumulative consumption (kWh/d)	26	65	45	136*
Share of total load per category (%)	22	48	30	100**

Table 4
Optimal architecture for microgrids with different PES allowed.

Percentage of energy shortage (%)	PV (kWp)	Battery (kWh)
0.1	57.1	493
1	47.3	367
3	42.3	298
5	40.4	265
10	37.4	209
15	34.5	192

constraints are illustrated in Table 4. At this stage, it is assumed that all users receive the same Quality of Service (QoS).

The results show that designs are highly impacted by the PES constraint. A microgrid designed for a PES of 0.1% requires more than twice as many batteries and 65% more solar panels as compared to a design with an allowed energy shortage of 15%.

4.2. Relation between LCOE and PES constraint

The LCOE for microgrids with different PES constraints are illustrated in Fig. 5. The PES is reduced by installing additional solar panels and batteries (see Table 4).

Additional generation equipment often produces electricity in excess of the demand, and when the battery storage is full, energy is lost (see Fig. 5). Indeed designs were optimised to minimise cost and not to avoid electricity loss. In some cases (designs with PES < 15% but also with a PES of 30%, 35%, 45% and 50%) a microgrid designed with fewer batteries and relatively more solar panels was able to meet the demand at minimal cost. This kind of adjustment between the number of solar panels and the number of batteries is responsible for the energy loss (due to excess production) that is observed. Microgrids that were designed to meet

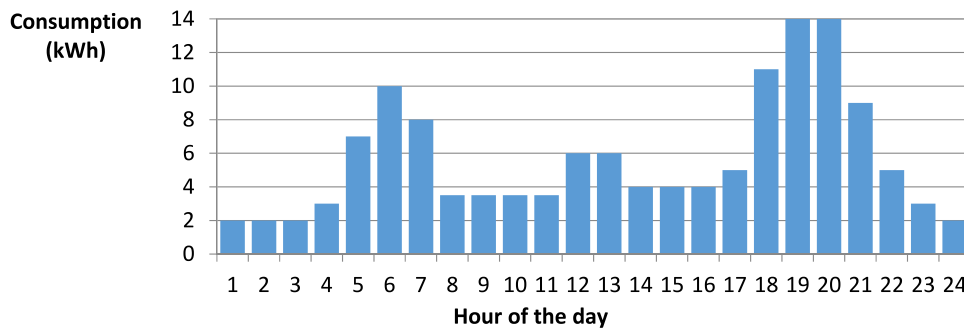


Fig. 4. Average daily consumption pattern for the 100 household community.

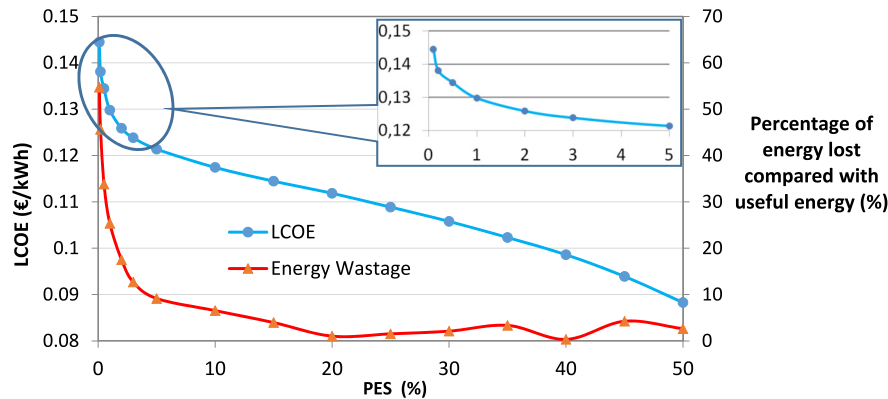


Fig. 5. Levelised Cost of Electricity (LCOE) and percentage of energy lost depending on the Percentage of Energy Shortage (PES) in the microgrid.

90% of the energy demand (PES constraint of 10%) produced 6.5% of energy excess beyond the energy consumed. The percentage of energy lost increased quickly as the microgrid was designed to meet the energy demand with lower PES: for a PES of 1%, the energy lost was 25% and for a PES of 0.1% the energy produced in excess represented as much as 55% of the useful energy. This can explain a sharp rise in LCOE for microgrids designed to supply the load with a maximal PES allowed inferior to 10%.

When the PES constraint decreased from 50% to 10%, the cost of electricity increased almost linearly. It became more expensive to reduce the PES further than 10% with the cost of electricity increasing non-linearly for lower PES constraints. Users have to pay 10% extra per kWh to secure a PES of 2% (at most), compared to a PES of 10%. Reducing the PES from 2% to 0.1% would result in a further increase of 20% of the LCOE. In other words, if users accept that the energy supplied by the microgrid falls short of an average of 2% compared to their need, 20% can be saved on their electricity bill.

The perspective of investors can be better represented by observing the impact of PES constraint on the Capital Expenditure (CAPEX) (see Fig. 6).

Since less electricity is available to users in microgrids with higher PES, the different CAPEX cannot be directly compared. Thus capital expenditures were divided by the amount of electricity effectively consumed by users (secondary vertical axis of Fig. 6). The results show that this CAPEX is highly influenced by the PES constraints for PES constraints inferior to 5%. For a microgrid designed with a PES of 0.1%, this CAPEX per unit of electricity consumed per year is 50% higher than for a microgrid with a PES of 5%. This shows that the choice of PES constraint is highly relevant from the investor's perspective, who can minimise the risk of their investments by reducing their capital investment.

It was shown in Robert and Gopalan (2018b) that the design of a solar, stand-alone microgrid depends mostly on the yearly

average solar irradiance and little on seasonal variations. Thus the results presented here are expected to be consistent, regardless of the location.

4.3. Choice of Percentage of Energy Shortage (PES) based on budget constraints

The monthly electricity bill was calculated for the three types of user assuming that they are connected to microgrids designed for different PES constraints (see Fig. 7). As mentioned in Section 2.4.2, it was assumed that electricity is sold at the LCOE (see Fig. 5) + 10%.

The results indicate that budgets of households are impacted significantly by a change in PES preference. Type 1 users can afford 0.75 kWh per day at a PES equal or greater than 15%, while Type 3 users can afford the highest level of reliability with only 0.1% of energy shortage. However, Type 3 users are unlikely to be satisfied with a low-cost microgrid delivering electricity with a PES of 15%. Thus, the results confirm that no single PES option can give satisfaction to all users.

4.4. Final microgrid design for multi-PES constraints

The final microgrid design was performed for two realistic scenarios. The overall PES constraint for the microgrid was calculated for two sets of assumptions (see Table 5). In both scenarios, Type 1 users were assigned a PES constraint of 15% which is the best QoS that they can afford such that their monthly electricity does not exceed 5% of their budget. Type 2 users, who can afford to spend more on electricity, were assigned a lower PES constraint. Type 3 users are assigned the highest QoS assuming that such users are business owners or entrepreneurs and that energy shortage would reduce productivity or income.

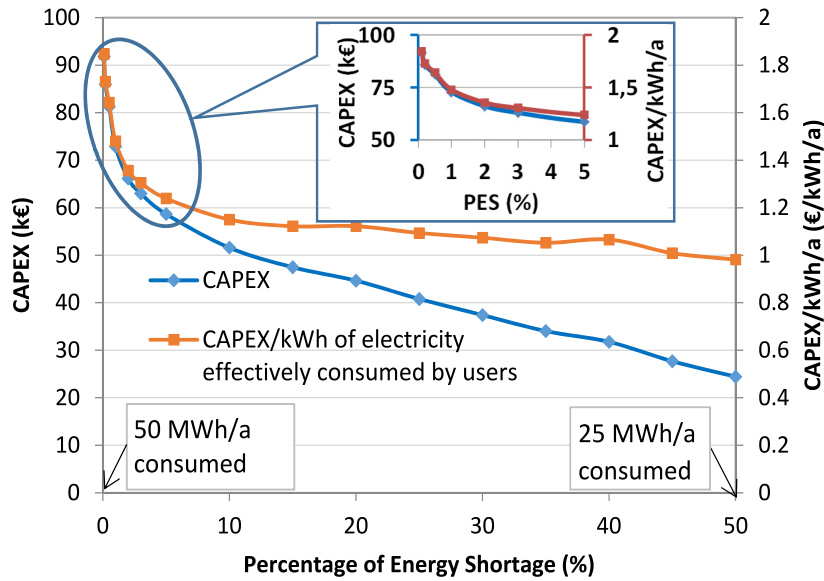


Fig. 6. Capital Expenditure (CAPEX) for microgrids, depending on their PES constraint (first axis) and considering electricity effectively consumed by users in a year (secondary axis).

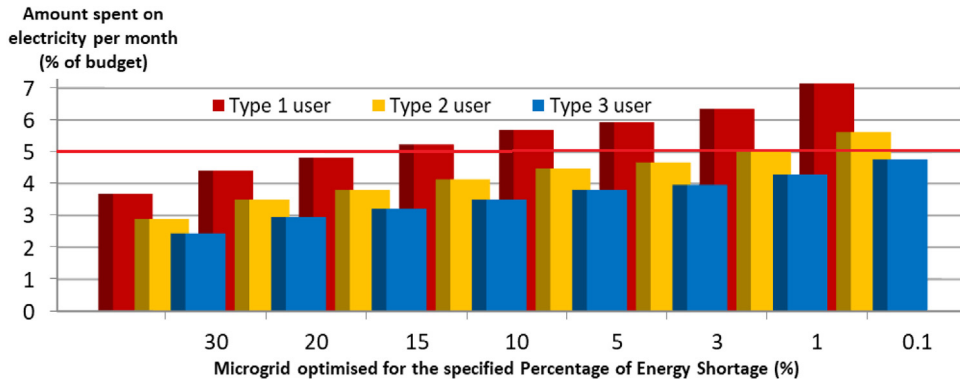


Fig. 7. Cost of electricity for each type of user when supplied by microgrids designed at different PES.

Table 5
Optimal PES option to maximise welfare.

Type of microgrid	Type of user	PES constraint (%)	Price per kWh (€/kWh)	Overall PES constraint (%)	Average price (€/kWh)
Optimal PES scenario 1	Type 1 user	15	0.126	7.80	0.131
	Type 2 user	7.5	0.131		
	Type 3 user	3	0.136		
Optimal PES scenario 2	Type 1 user	15	0.126	5.04	0.136
	Type 2 user	3	0.136		
	Type 3 user	1	0.143		

The optimal microgrid had an overall PES constraint of 7.8% in scenario 1 and 5.04% in scenario 2. In both cases, 35 low-income households were supplied electricity for less than 5% of their household budget. The 15 critical users received a reliable supply at a PES of 3% or 1% for a price of €0.143/kWh (Rs 11/kWh) at the highest.

The proposed method improves user satisfaction since users pay only for the QoS affordable to them. The risks of users

dropping out due to inability to pay, and of critical users investing in private back-up are decreased. Since users can benefit from a reliable connection, Multi-PES microgrids may also limit the migration of the high income inhabitants' towards cities, thereby contributing to the development of a more balanced society (Tacoli et al., 2015). On the contrary, if microgrids are designed with PES constraint such that electricity is affordable to all, Type 3 users will incur losses due to power interruptions and might migrate towards a city in search of proper infrastructure. The alternative for Type 3 users would be to invest in a private back-up. This alternative was compared to the proposed multi-PES microgrid.

4.5. Cost effectiveness of multi-PES microgrids compared to a private energy back-up for Type 3 users

Without multi-PES microgrid, the solution could be to design affordable microgrids (with PES constraint of 10% or more), but leading to the dissatisfaction of critical users who might choose to invest in private back-up solutions. Two additional simulations were performed assuming a microgrid with a PES constraint of 10% as a base case and unsatisfied Type 3 users investing in a private back-up system. In the first case a diesel generator ensured that the full energy demand was met. In the second case, batteries were dimensioned such that the PES was 0.2% at most.

Table 6

Cost of individual back-up for Type 3 users compared to a microgrid with a PES of 0.2%.

	Diesel generator (1 kW)	Batteries (1 kWh)	Cost of electricity (€/kWh) ^a	PES (%)
Base case with PES 10% Upgraded microgrid design	0	0	0.129	10
Base case with private back-up	1	0	0.195	0
	0	5	0.168	0.2

^aThe electricity coming from the microgrid was assumed to cost 10% more than the LCOE calculated by the software to account for the operational cost such as metre cost, maintenance of the distribution grid and payment collection cost.

The cost of using a diesel generator for back-up was calculated assuming a diesel generator of 1 kW costing €135 and a fuel cost of €0.9/l, other assumptions are as per the inbuilt model of a generic diesel generator in HOMER. An alternative back-up was based on battery. The batteries described in Section 2.2 were used together with an inverter of 1 kW at €65. The results of the simulations are shown in Table 6. They confirm that an individual back-up is not economical compared to a very reliable microgrid. Thus the proposed multi-PES microgrid is a more cost effective option than private back-up systems.

5. Conclusion and future work

The preliminary results of this work highlighted that in RE microgrids, the degree of flexibility of users can have a great impact on their electricity bill. It was shown in the test scenario, that when users accept that the energy supplied by the microgrid falls short of an average of 2% compared to their need, 20% can be saved on their electricity bill. The second contribution of this work is a sustainable method for the design and operation of rural communities, which addresses one of the main causes of business failures in stand-alone microgrids today: the diversity of expectations in terms of reliability of supply and cost of electricity. The proposed multi-PES microgrids satisfy simultaneously a range of users and therefore limit the risk of business failures caused by dropouts and unreliable electrical supply. A realistic scenario demonstrated that “energy shortage service differentiation” is viable and a cost effective solution for rural electrification. As RE generation share is increasing in the global energy mix, this works suggests that incentives are expected to rise for demand response schemes.

Work is on-going to design a demand response system that can warn users and anticipate energy shortage due to bad weather. The objective is to reduce coping cost and discomfort due to energy shortages. A model to evaluate loss-of-utility due to energy shortages is under development. Another interesting future work will be to integrate energy exchange possibilities where users can sell parts of their energy quota to others (Alam et al., 2017; Giusti et al., 2014).

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