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Article

Microgrid as a Cost-Effective Alternative for Rural Network Underground Cabling for Adequate Reliability

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Abstract: Microgrids can be used for securing power supply during network outages. Underground cabling of distribution networks is another effective, but conventional and expensive alternative to enhance reliability of power supply. This paper presents firstly an analysis method for the determination of microgrid power supply adequacy during islanded operation, and secondly, a comparison method for overall cost calculation of microgrids vs. underground cabling. The microgrid power adequacy during a rather long network outage is required in order to indicate high level of reliability of supply. The overall cost calculations consider the economic benefits and costs incurred combined for both the distribution network company and the consumer. Whereas the microgrid setup determines the islanded operation power adequacy and thus the reliability of supply, the economic feasibility results from the normal operations and services. The methods are illustrated by two typical, and even critical, case studies in rural distribution networks: an electric-heated detached house and a dairy farm. These case studies show that even in case of a single consumer, a microgrid option could be more economical than network renovation by underground cabling of a branch in order to increase reliability.

Keywords: battery energy storage system (BESS), PV, micro CHP, microgrid, islanded operation, distribution network, network outage, reliability, underground cable

1. Introduction

By definition, a microgrid is a cluster of sources, storage systems and loads, forming a semi-autonomous, controllable, and flexible small electrical entity at the connection point towards the wider power system [1,2]. The capability to operate at times as an intentionally disconnected island from the rest of the power system was added to the definition of a microgrid only later [3,4]. As a microgrid has a variety of operational functions and technical requirements, microgrid systems become complex [5].

Potential microgrid revenue streams that can offset investment and business-as-usual costs according to [5] are:

- Participation in Demand Response programs;
- Export of on-site generation to the electricity grid;
- Reduced costs due to added resiliency against outages and lost loads;
- Participation in local microgrid energy markets.

The profitability possibilities of residential microgrids as aggregator-based solution from the perspective of different stakeholders, e.g., utility, aggregator, and prosumer, were analyzed in [6]. The feasibility and profitability of microgrids participating in primary frequency control reserve (FCR) market through an aggregator were assessed in [7]. Furthermore, [8] analyzed battery energy storage system (BESS) usage on the frequency regulation market.

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According to [9] underground cabling of the network is an effective way for distribution system operators (DSOs) to increase the reliability of power supply. However, underground cabling is expensive.

Today, farming is highly automated and electricity dependent [10] and even short power interruptions are very detrimental. Farming is an energy intensive industry [11], and thus farmers value reliability of electricity supply more than most of the other customer groups.

Farms are located naturally in rural areas, possibly on the long distribution network radial branches with low electricity customer density. The majority of farmers have back-up generators (e.g. [11]). Farmers having own power production to cover a portion of their electricity need is gaining popularity.

Several recent studies have focused on microgrid islanded mode operation, microgrid energy management system, and power supply adequacy and forecast, e.g. [12–14]. Ref. [12] assessed power supply capability in islanded mode operation within a couple of hours by using a simulation time step of maximum 1 minute. Electro-technical aspects of an unexpected microgrid islanded operation were also analyzed in [14] while considering optimal energy management of the microgrid and anticipating an outage at any hour. Grid-connected microgrid economic operating strategy was proposed in [15] to minimize the operating cost for the operating period of 24 hours-ahead.

Characteristics of, e.g. the Finnish rural medium voltage (MV) networks are long distances and low loads, and thus, underground cabling to increase reliability is not an economical option as-is for the distribution network development. However, the legislation steers towards underground cabling and cabling is incentivized by the regulation framework.

Ref. [16] posed a question, on which reliability indices the network development actions actually should be based on, optimizing the number of faults, duration of faults, outages cost, or yet on some other index. The indices in several Finnish studies considering the economics of cabling and increasing reliability of power supply, are based on the results and data of a study from 2005, and the regulation model framework, e.g., [16–19]. The studies evaluate the DSO investment profitability only compared to the outage costs (or cost of energy not supplied, CENS). The customer-side and possible co-operative technical and shared economic alternatives have not been considered.

Studies have shown other alternatives' feasibility potential instead of underground cabling, e.g., BESS as back-up to cope with short interruptions up to a couple of hours, [19,20]. BESS sizing methods in different microgrid application have been reviewed in [21], and [22] presented an analytical approach in general level for the sizing of a backup storage unit.

The legislation and regulation - as subject to changes - are omitted in this study. Compared to network cabling, the primary focus is on using microgrids as a means to increase consumer reliability of power supply in addition to increasing energy self-sufficiency of the prosumer, and possibly benefit from other revenue streams. Microgrid option being the overall optimal economic solution, it would provide cost reductions either for electricity users, the DSO, or both. The incentives and possibilities to invest in microgrids, however, might not be common for all the relevant stakeholders.

This paper presents a cost and performance analysis of microgrid to be enabled up to a few days islanded operation compared to underground cabling option as means to reach a high level of reliability of power supply. Two case studies of typical and significant rural customers are analyzed for demonstrating the assessment framework and to illustrate the potential economic feasibility of the microgrid option over underground cabling.

Section 2 presents background information for the framework, the assessment method for microgrid power adequacy is presented in section 3, the economic comparison method in section 4, the case studies data is given in section 5, and the results in section 6. Finally, the results are discussed in section 7 and conclusions are provided in 8.

2. Distribution networks, reliability and microgrids – formation of the case studies

General distribution network cabling and reliability issues, especially in Finland where the study cases are located, are discussed in section 2.1, background for the microgrid cases for the study in section 2.2, electricity market data in section 2.3, covering general consumer electricity purchase and small-scale producer electricity sales, as well as other possible microgrid income options.

2.1. Distribution network reliability and underground cabling

The maximum interruption duration to be endured is difficult to determine. The average interruption duration may be only a few hours, but individual interruptions may last for several days. The probability of short interruptions is higher, but long interruptions cause bigger damages to consumers. The required BESS back-up power supply capacity and related costs depend greatly on the dimensioning interruption duration. A relatively long network outage durations should be considered, and thus up to a few days duration is assumed in this study.

Farms in practice invest in a reserve power generator sets to prepare for outages. A simple generator set with low investment cost is assumed in this study (see Appendix A).

A DSO considers profitability and costs from its own perspective in accordance to the regulation, and the consumers consider their own finances. In the alternative method presented in this paper, specific network cabling case overall costs are compared in a straightforward manner to the microgrid option overall costs, combining the costs of the consumer/microgrid owner and the network company. The data used is presented in Appendix A. Cable costs are rough mean costs of the cost data used in the network regulation model in Finland [23].

2.2. Microgrid case studies

Small microgrids consisting of a single customer or a few of them, most likely will require a BESS and some local electricity production in order to guarantee reliability of supply in islanded operation. The microgrid profitability increases the more useful functions the microgrid and its components have.

In addition to BESS contributing to secure power supply during network outages, it would be used for balancing own power production with consumption, and enable to handle electro-technically the microgrid islanded operation in a stable manner. Appropriate measures and careful technical planning is required, but the technical and control aspects are not considered in this study.

The selected case studies are (i) a large dairy farm and (ii) a regular size detached house with electric heating. The case studies reflect well the typical rural area electricity users and the main customer groups, and are among those with most critical needs of uninterrupted electricity supply within the respective customer groups.

Both case studies include a BESS and PV production. In addition the farm has a micro CHP plant operating with wood chips (which technology feasibility is already proven). Microgrid data is provided in Appendix A.

2.3. Electricity market data

For the electricity consumption, general electricity cost and distribution fee in Finland are considered. The possible excess power in the microgrid can be sold to the network, and typical electricity price and power transmission fee for grid-infeed power are considered. The electricity purchase and sales figures presented in Appendix A are roughly estimated based on recent historical prices in Finland. Small-scale production of electricity to one's own use in Finland is tax free.

Relevant reserve market and revenue possibility for the microgrid with BESS capacity is on the frequency control reserve for disturbances (FCR-D). Prosumer participation to the reserve market would take place via an aggregator service provider (e.g., as in [6,7]), which would take care of the formalities against a reasonable fee for the services. This fee is expected to be relatively small and thus is now omitted in the calculations.

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Load response could be an opportunity also for earnings as a system service, as well as a means to prioritize produced electricity own use and minimize exchange of electricity with the network. Demand response or load control was not considered for simplicity in this study.

3. Electricity supply adequacy assessment in microgrids during network outages

The microgrid electricity supply adequacy is assessed considering a full year from an hour to hour. For the assessment, hourly data and simulation is used. Intra-hour variability and control is assumed to be able to be handled with the BESS and other possible microgrid components. Hourly time sampling is needed in order to catch the variability of PV generation, diurnal electricity consumption behavior in addition to seasonal and weekly variations, combined with the requirement of having sufficient electricity supply to meet the consumption at all times during network outages.

The calculation of the power supply adequacy is implemented in a MATLAB script. The general, normal state, analysis is described in section 3.1, and section 3.2 describes the subroutine for the islanded operation calculations.

3.1. Microgrid operation under normal state

The principles of the proposed calculation procedure are presented by a flowchart in Figure 1. In order to prepare for an unexpected network outage taking place at any time, a minimum charge in the BESS is maintained. The minimum charge may be, e.g., a fixed constant charging level of the BESS throughout the year, dependent on the historical electricity usage, or dependent on the time of the year. The momentary BESS charge level can be i) at minimum charge limit, ii) below observation hour minimum charge limit, iii) fully charged, or iv) between the minimum limit and full. Considering the observation hour electricity consumption and total own power production, the BESS is charged and discharged depending on the status of the BESS, and the microgrid electricity deficit or surplus. For simplicity, this is not depicted in the flowchart.

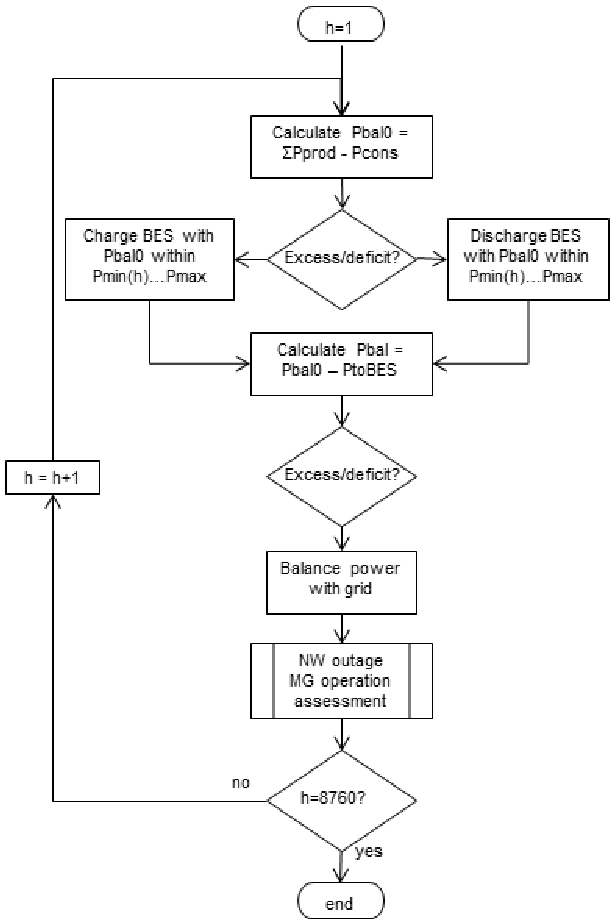

Figure 1. The procedure used in the MATLAB script for calculating the hourly power balance and power supply adequacy throughout the year in normal operation.

3.2. *Microgrid operation during network outage*

The microgrid should be prepared for a network outage at all times. The duration of the possible outages are unknown. As the microgrid option (to increase reliability of power supply) is compared to the distribution network underground cabling option, the microgrid power supply adequacy should reflect similar reliability as that of the cabled network. Thus a couple of days islanded operation capability is used as the target.

In an islanded mode operation, the micro CHP plant is assumed to be able to put in operation within an hour and it would be able to produce maximum electric power during islanded operation.

The microgrid options – by varying different parameters and assumptions used – can be assessed for the duration of power supply adequacy over the whole year, for each hour of the year. Section 3.1 and flowchart in Figure 1 presented the calculations for the normal states, and thus the initial situations for the microgrid islanded operation for each hour of the year. Flowchart in Figure 2 presents the calculation procedure ("MW outage MG operation assessment" sub-procedure in Figure 1 flowchart) for the assessment of microgrid islanded mode operation and electricity supply adequacy for each respective hour.

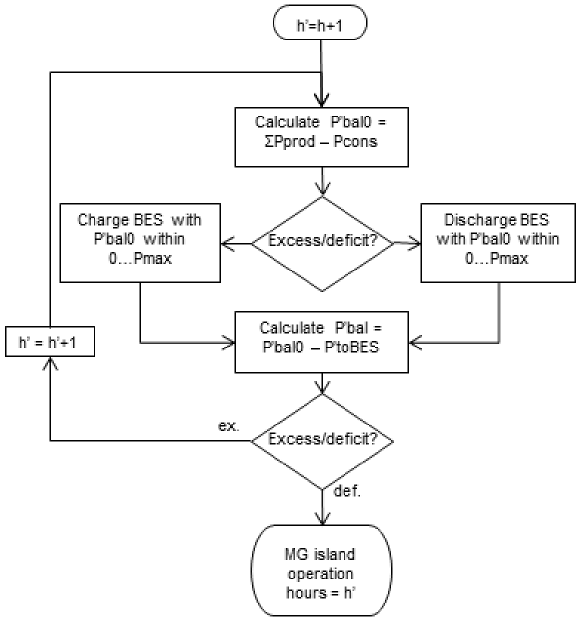

Figure 2. The MATLAB script sub-procedure for calculating the power supply adequacy and maximum duration in islanded operation.

4. Overall economic comparison and economic influence on stakeholders

The DSO's regulated monopoly business is to provide electricity consumers sufficiently reliable electricity distribution at a reasonable fee. Network company business should also be a profitable for the company owners.

Interest rate of 2 % is used. For all the investments, equivalent annual costs are calculated, thus enabling the comparison of costs in an annual level. Value added tax in Finland applicable for most of the relevant taxed items is 24 %. For simplicity, this tax rate is used in the calculations for all the taxed items.

The calculations for the overall economic comparison of the underground cabling and microgrid options are described in section 4.1. In addition, the cabling investment and microgrid option economic influence on the different stakeholders (the network company, the consumer, and the state) are presented in section 4.2.

4.1. Calculations for the overall economic comparison

The overall economical option is determined by comparing the equivalent annual cabling option index costs $C_{cab,ann,TOT}$ and microgrid option index costs $C_{MG,ann,TOT}$.

Consumer power purchase from the market, and thus the electricity delivered by the network company to the consumer/prosumer affects the network company income from power distribution. As an income to the network company, it is an expense to the consumer. If considering both in the overall economic calculations, distribution fee (which could be even large) would be cancelled out and the distribution fee would not affect the results. The interest of the consumer is considered more significant, and in this context the aim should not be to increase network company income by cabling investments (indirectly through regulation) or prevent decrease of income over possible consumer benefits. Furthermore, the consumer could become a prosumer regardless of the cabling or other means of securing the power supply, e.g. by microgrid option and BESS. Therefore, "index costs", omitting the DSO power distribution income in the overall economic calculations are being used for the comparative purposes of the two options.

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4.1.1. Underground cabling option

In the underground cabling option, only the investment cost on the cable and the cable trench are considered according to the specified price data provided by the Finnish energy authority. Other component investments are omitted. In the illustrative farm case study an investment on a 20 kV cable of 10 km is considered, and in the detached house case study an investment on a 0.4 kV low voltage cable is considered. The cable investment equivalent annual cost $C_{cab.inv,ann}$ is calculated.

The consumer costs in the cabling option consist of the total annual electricity costs, $C_{cons.cab}$, including the energy purchase from the market and power distribution fee. In addition a consumer investment cost, $C_{gs.inv,ann}$, of the mandatory generator set for reserve power during outages is considered in the farm case study. The expenses of the possible use of this generator set are omitted.

Thus, the total index costs of cabling option for the comparison are

$$C_{cab,ann,TOT} = C_{cab.inv,ann} + C_{cons,cab} + C_{gs.inv,ann}. \quad (1)$$

4.1.2. Microgrid option

The microgrid option costs consist of the investment costs on the BESS ($C_{BESS.inv,ann}$), PV ($C_{PV.inv,ann}$), and CHP power plant ($C_{CHP.inv,ann}$) as the appropriate share of total plant investment on electricity production (electricity production capacity per total electricity and heat production capacity), all expressed as equivalent annual costs. Other costs consist of annual maintenance with CHP plant fuel-related expenses etc. (C_{maint}) and electricity purchase cost ($C_{cons,MG}$) including energy and power distribution fees. The possible prosumer income from surplus electricity sales (Y_{prod}, with transmission fees subtracted) and system services (Y_{serv}) are also considered in the cost calculation.

The total index costs of the microgrid option for the comparison are

$$C_{MG,ann,TOT} = C_{BESS.inv,ann} + C_{PV.inv,ann} + C_{CHP.inv,ann} + C_{maint} + C_{cons.MG} - Y_{prod} - Y_{serv}. \quad (2)$$

4.2. *Economic influence on the relevant stakeholders*

The underground cabling and microgrid option may have different influence on the different stakeholders. The same calculation data as in section 4.1 is used for the assessment of economic influence of the two options on different stakeholders, DSO, consumer/prosumer, and the state.

4.2.1. Distribution system operator

A rough assessment of direct economic influence of the cabling and microgrid options on the DSO income are calculated as

$$\begin{cases} Y_{DSO,cab} = Y_{dist.fee,cab} - C_{cab.inv,ann} \\ Y_{DSO,MG} = Y_{dist.fee,MG} + Y_{trans.fee,MG} \end{cases}, \quad (3)$$

where $Y_{dist.fee,cab}$ and $Y_{dist.fee,MG}$ are the distribution net income of the power supplied to the customer in the cabling and microgrid options respectively, and $Y_{trans.fee,MG}$ is the power transmission net income of the microgrid power fed to the grid.

4.2.2. Consumer / prosumer

All the microgrid investments and costs are assumed to be covered by the consumer/prosumer. The economic influence of the cabling and microgrid options for the consumer/prosumer as costs are thus

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$$\begin{cases} C_{pros,cab} = C_{cons,cab} + C_{gs.inv,ann} \\ C_{pros,MG} = C_{BESS.inv,ann} + C_{PV.inv,ann} + C_{CHP.inv,ann} + C_{maint} + C_{cons,MG} - Y_{prod} - Y_{serv} \end{cases}. \quad (4)$$

4.2.3. State

The economic influence of the alternative options on the state tax income may be relevant for a consideration. The very rough estimates are calculated for the assessment of comparison of state tax income level in the cabling and microgrid options in order to get indication of possible significant differences. The calculations are with total component investment costs *C* and lifetimes *L*

$$\begin{cases} Y_{tax,cab} = \frac{s}{1+s}\left(\frac{C_{cab,inv}}{L_{cab}} + \frac{C_{gs,inv}}{L_{gs}} + C_{cons,cab}\right) + t_{el}E_{cab} \\ Y_{tax,MG} = \frac{s}{1+s}\left(\frac{C_{BESS,inv}}{L_{BES}} + \frac{C_{CHP,inv,el}}{L_{CHP}} + \frac{C_{PV,inv}}{L_{PV}} + C_{cons,MG} + Y_{prod} + Y_{serv}\right) + t_{el}E_{MG} \end{cases}, \quad (5)$$

where s is value added tax, t_{el} the electricity tax, and E_{cab} and E_{MG} the electricity bought from the grid in cabling and microgrid cases respectively.

5. Microgrid data and specifics for the case studies

The case study loads are described in section 5.1, BESS units in section 5.2, PV production in section 5.3 and the CHP power plant in section 5.4. The technical and economic data specifics and parameter values for the case studies are presented in Appendix A.

5.1. *Electricity consumption*

A pre-determined hourly data series of electricity consumption was used. The consumption was considered independent from the microgrid operating state – network connected or islanded operation. Load was not controlled in order to obtain longer islanded operation capability, nor to minimize power exchange with the network in normal state.

In addition to electric heating, the detached house has a fireplace for heating. Thus, it is a rather typical house in rural areas in Finland with high electricity consumption of approximately 14 MWh/a. Actual historical electricity consumption data series of a consumer was used.

The dairy farm case was with about 180 cows and corresponding electricity consumption of approximately 261 MWh/a. The farm data series was created based on data from similar size farms. Daily consumption profile was based on diurnal consumption data of a large cowhouse in a winter day, and the variation from day to day throughout the year was approximated by creating sliding data series based on monthly electricity consumption. The dataset was then suitably scaled for the specified annual consumption.

5.2. BESS units

Despite the significant difference in annual electricity consumption, both case studies were assumed with identical BESS units due to the backup power supply need during long network outages.

The calculations presented in this paper do not consider a decrease in electric capability of the BESS units over time. The data was estimated based on the recent global BESS market trends, and the investment costs may easily change. In addition the cost range of used prices has been rather broad in different studies (e.g., [19,20]).

Different BESS minimum charge principles were determined for the case studies. In the farm case the minimum charge was predetermined as function of the electricity consumption, ranging from 50 % of $E_{max,BESS}$. to $E_{max,BESS}$. The hourly minimum was determined by a scaling coefficient calculated as a sliding average of the electricity consumption of 24 previous hours.

For the detached house, the BESS minimum charge was predetermined by assessing the consumption and production data. During high consumption and low PV production at winter months, December and January, the limit was set to $E_{max,BESS}$, and 75 % of $E_{max,BESS}$ during the low

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consumption and high PV production in the summer time approximately from March to October. For the other times the limit was determined by linear interpolation between 75 % and 100 % of $E_{max,BESS}$.

In normal operation, the BESS charging level was at least the minimum charge at all times, i.e. at least 50 % in the farm case and 75 % of $E_{max,BESS}$ in the detached house case. Thus, quite large amount of energy is stored in the BESS and it would be able to provide nominal power easily for a short period of time (from seconds to minutes) without discharging significant portion of energy. Therefore, the BESS minimum charge was considered to be sold as FCR-D reserve on an annual agreement. In the case studies the BESS is charged at least at specified minimum charge level 100 % of the time (excluding possible network outage and post-outage periods). There may be times when the BESS charge cannot be available or is fully needed for the preparation of islanded operation and thus the BESS capacity is assumed to be sold to FCR-D market only 7000 h/a in the study cases. The possible income for activated FCR-D reserve capacity was not taken into account in the calculations.

5.3. PV production

An hourly PV production data series was created for a specific location (in Finland) based on MERRA-2 time series data on radiation [24] and air temperature [25]. The daily average radiation and temperature were scaled to match monthly values from PVGIS database [26,27]. PV panel generation (in per units) was calculated considering location and temperature, and selected panel tilt given by PVGIS "optimal inclination angle". The PV generation data series was then scaled appropriately for the selected PV capacity in the case study. The same per unit dataset was used for both the detached house and the farm.

5.4. Micro CHP production

Gasification based CHP power plants have a cold start time of less than an hour and controllability of 1 kW/s. Furthermore, a wood chip fueled CHP plant can be controlled, whereas its optimal production level and electricity production depends also on heat demand.

For this case study – combined with substantial PV production and BESS – the CHP plant was offline during the warm and sunny summer period. At other times, its production was scaled according to pre-determined data series based on the annual total production of 150 MWh, and a scaling coefficient. The coefficient was determined for each hour as a sliding average of the electricity consumption of 24 previous hours.

In the case of network outage occurring and CHP plant being offline, the CHP plant is assumed to be started within one hour to support the microgrid islanded operation power supply.

6. Case study results

The assessment of the microgrid configuration for acceptable reliability of power supply were done based on the procedure described in section 3, and the results are presented here in section 6.1. The calculations for economic comparison of the microgrid and underground cabling option were done in accordance to section 4.1, and the influence on different stakeholders was assessed based on section 4.2. All economic calculation results are presented in section 6.2.

6.1. Analysis of reliability of power supply

With the specified and adjusted assumptions and data, the microgrid electricity consumption, and electricity production hourly data curves for the whole year are presented in Figure 3(a), the BESS charging level in Figure 3(c), and the power feed-to and in-take-from the network are presented in Figure 3(e) for the farm case. The corresponding data for the detached house case are presented in Figure 3(b), 3(d) and 3(f) respectively. The total consumption and power production of the case study microgrids are presented in Table 1.

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Table 1. Microgrid consumption and production in the case studies.

Case study	Cons. [kWh/a]	Prod. [kWh/a]
Farm	275 028	192 288
Detached house	14 119	4 229

Analysis of islanded operation throughout the year for each hour indicated that the microgrid electricity supply would be sufficient during an interruption at minimum 58 hours in the farm case and 41 hours in the detached house case. The islanded operation capability incidents were binned based on the duration of the adequate power supply. The numbers of occurrences with the shortest durations are presented in Table 2. The rest of the hours of the year, power adequacy was sufficient for more than 3 days.

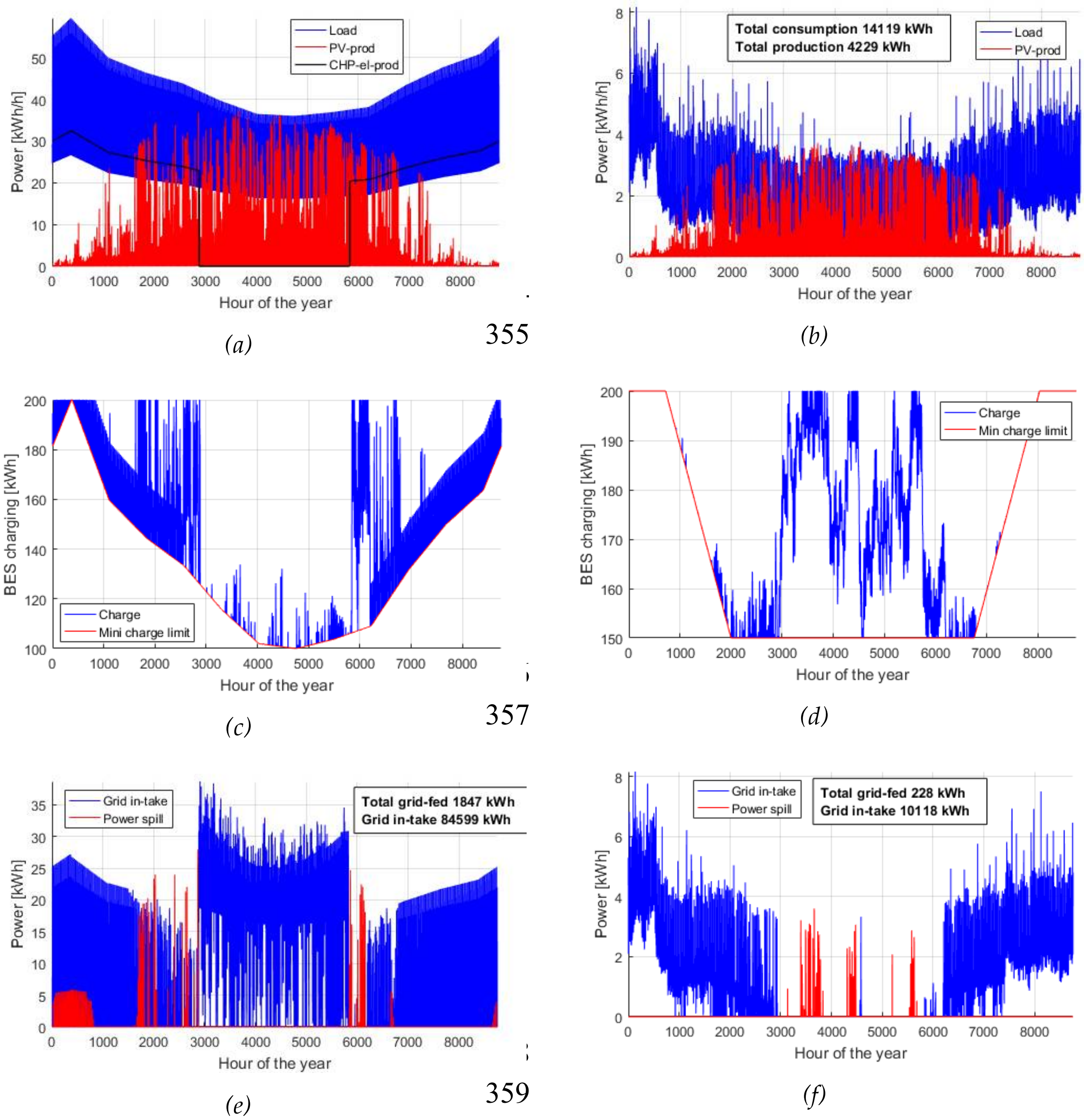

Figure 3. Farm and detached house case study hourly input and result data series for the study year: electricity consumption and production (a - farm, b -detached house), BESS charging level between

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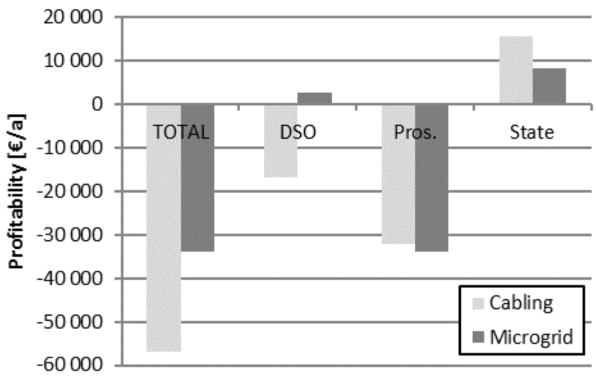
dynamic minimum charge level and P_n (c - farm, d - detached house), electricity taken from and fed to the grid (e - farm, f - detached house).

Table 2. Case study microgrid islanded operation with adequate power supply if less than 3 days.

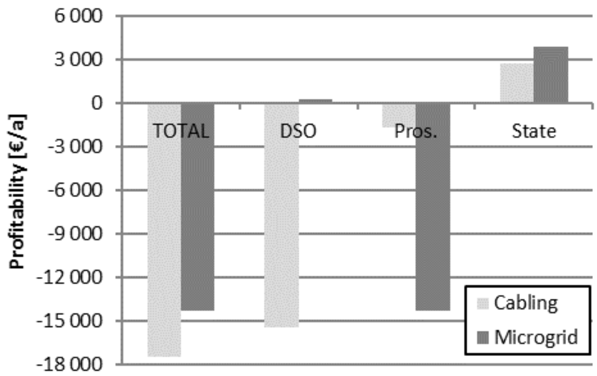
Capability duration	Farm		Detached house	
	Number of occurrences	% of year	Number of occurrences	% of year
<12 h	0	0.0 %	0	0.0 %
12…<24h	0	0.0 %	0	0.0 %
24h…<2days	0	0.0 %	272	3.1 %
2…<3 days	87	1.0 %	593	6.8 %

6.2 Calculations for economic comparison

The total equivalent annual costs for the cabling and microgrid option were calculated with (1) and (2). In addition, the economic influence of the options was assessed individually on each stakeholder by (3) to (5). The case study results are presented and compared in Figure 4.



(a)



(b)

Figure 4. Cabling and microgrid option total costs, as well as economic influence on the DSO, consumer/prosumer, and the state in (a) the farm case study, and (b) detached house case study.

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7. Discussion

A number of assumptions were considered, especially regarding the calculation of economic comparison of microgrid option with a distinct underground cabling investment option. The results provide insight for further studies and indication of the results.

The two case studies were a single consumer detached house and a farm. Despite almost 20-fold difference in electricity consumption and own PV production of appropriate capacity, both prosumers required identical BESS capacity in order to able to reach approximately the same and sufficiently high level of reliability of power supply in case of network outages. This result implies that own variable production combined with storage may not be sufficient or profitable solution to guarantee reliability of supply in the case of long network outages.

In the farm case study, the total costs of the microgrid option are significantly smaller than in the cabling option, thus favoring the microgrid as a means to cope with the reliability of power supply instead of cabling. The most of the costs would be covered by the prosumer. In addition, the microgrid option – with the given assumptions – would be slightly more expensive for the prosumer. The DSO's income is negative in the cabling case, but positive in the microgrid case. Thus, the benefit and the costs could be shared between the DSO and the prosumer. In the case of the microgrid option, the state tax income would be somewhat smaller than in the cabling option in the reasonable case of the farm.

The total costs in the detached house case also indicate the microgrid option to be more economic one. However, the costs would be practically totally covered by the prosumer, and the BESS investment is extremely expensive compared to the prosumer annual costs in the cabling alternative. Thus, this option is not feasible as-is.

8. Conclusion

Microgrid in rural area could be an economic alternative to underground cabling in specific cases. Underground cabling being costly to the DSO, the microgrid BESS could be partially or fully invested on by the DSO in order to make the microgrid option profitable also to the consumer besides the DSO.

Furthermore, combining controllable generation into a microgrid in addition to weather dependent generation, results in a more feasible solution and enables a reasonable duration of islanded operation.

The microgrid option would be a solution based on a willingness and common understanding between the DSO and the consumer, among the relevant stakeholders and is a question of shared benefit that also depends on the network company regulation model and its development

Author Contributions: The literature review, modeling, simulations, and the analysis was done by Sanna Uski. Erkka Rinne created the PV data set and provided the relevant description for the manuscript. Sanna Uski prepared the manuscript and Janne Sarsama contributed on the revision of the manuscript especially on the reliability issues.

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Appendix A

Table A.1 Cabling option case study data assumptions.

Mandatory farm gen-set:		
$C_{inv,gs}$	investment cost for mandatory gen.set	4 000 €
L_{gs}	expected lifetime / investment period	10 a
Cable investment data:		
$C_{inv,cab}$	investment cost for MV (20 kV) cable[1)]	55 000 €/km
$C_{inv,cab}$	investment cost for LV (0.4 kV) cable[1)]	35 000 €/km
x_{cab}	used cable length in the investment	10 km
L_{cab}	expected lifetime / investment period	40 a

[1)] excluding tax

Table A.2 Microgrid option case study data assumptions.

PV:		
$P_{PV,f}$	farm PV rated power	50 kWp
$P_{PV,h}$	detached house PV rated power	5 kWp
L_{PV}	expected lifetime / investment period	30 a
$C_{inv,PV,f}$	investment cost for PV 50 kWp (10-250 kW cost level)	60 000 €
$C_{inv,PV,h}$	investment cost for PV 5 kWp (few kW cost level)	10 000 €
CHP:		
$P_{CHP,el}$	CHP rated electrical power	40 kW
	($P_{CHP,TOT}$ 140 kW; $P_{CHP,heat}$ 100 kW)	
$E_{CHP,ann}$	annual electricity produced in the study year	150 MWh/a
	CHP power plant investment cost	400 000 €
$C_{inv,CHP}$	electr. share of CHP plant investment cost	114 285 €
L_{CHP}	expected lifetime / investment period	30 a
C_{fuel}	approximated annual cost for fuel (wood chips)	2 800 €
C_{maint}	estimate for other annual maintenance costs	1 000 €
BESS:		
$P_{max,BESS}$	maximum power for charging/discharging	100 kW
$E_{max,BESS}$	maximum/nominal charge	200 kWh
L_{BESS}	expected lifetime / investment period	10 a
$C_{inv,BESS}$	investment cost for the BES (100 kW, 200 kWh)	144 000 €
FCR-D reserve market data for the study cases:		
p_{FCR-D}	FCR-D reserve capacity market price for annual agreements in 2017	4.7 €/MW,h
$P_{BES,FCR-D}$	BES capacity available to FCR-D reserve market	100 kW
$T_{BES,FCR-D}$	availability of BES for FCR-D reserve market	7 000 h

Table A.3 Electricity market and other economics data assumptions.

Retail electricity costs:		
$C_{el.ret}$	retail electricity price for consumer	0.05 €/kWh
$C_{el.trans}$	electricity distribution price for consumer	0.065 €/kWh
$C_{el.sold}$	price paid for sold electricity for prosumer	0.027 €/kWh
$C_{el.s.tr}$	electricity transmission price for prosumer	0.0007 €/kWh
t_{el}	electricity tax (included in electr. distrib. fee)	0.02253 €/kWh
Economics calculation parameters:		
r	interest rate	2 %
s	value added tax	24 %

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