Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment, Transport, Energy and Communications DETEC

**Swiss Federal Office of Energy SFOE**
Energy Research and Cleantech

# SWEET Call 1-2020: SWEET EDGE

# Deliverable report

| | |
|---|---|
| **Deliverable n°** | 5.14 |
| **Deliverable name** | Report on the suitability of microgrids for Switzerland |
| **Authors**<br>The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom. | Nicolas Stocker, ZHAW, **nicolas.stocker@zhaw.ch**<br>Michael Wild, ZHAW, **michael.wild@zhaw.ch**<br>Jürg Rohrer, ZHAW, **juerg.rohrer@zhaw.ch** |
| **Delivery date** | February 2024 |

The research published in this report was carried out with the support of the Swiss Federal Office of Energy SFOE as part of the SWEET EDGE project. The authors bear sole responsibility for the conclusions and the results.

This report was originally written in German, and parts of it have been translated using third-party software.

Zürcher Hochschule für Angewandte Wissenschaften
Life Sciences und Facility Management
IUNR Institut für Umwelt und Natürliche Ressourcen

sweet swiss energy research for the energy transition

## Table of contents

## Summary

There is an increased focus on electric distribution grids caused by the energy transition, leading to electrification of mobility and heating and the massive upscaling of decentralized renewable electricity generation. Smart grid[1] technologies and applications make the distribution grids more transparent and active. Microgrids[2] are brought up in this regard as as a means to improve key performance metrics of distribution grids such as their reliability, efficiency, cost, and local participatory concepts.

While much of the existing research on the viability of microgrids approach the problem generically, the costs and benefits of microgrids depend on the local energy system with a special importance on the characteristics of the electric power grids. Because these factors differ substantially by country, an analysis of the suitability of microgrids for Switzerland is presented in this report.

Clarifying the role of microgrids in the Swiss energy system is of importance due to the high costs involved in grid development, the need for long-term planning and investment, and the fact that power grids are a key factor in the energy transition. This study compares preconditions and benefits of microgrids, as known from literature and existing projects, against the realities within the Swiss energy system.

The analysis has revealed that, aside from niche applications, the utility of microgrids within the Swiss energy system is currently limited. This is primarily because many of the general advantages of microgrids are not realized due to the strong performance and high coverage of the existing Swiss power grid. Furthermore, there are benefits that can be achieved through well-developed smart grids with a better cost-benefit ratio, especially the local, temporal balancing of consumption and production.

The results show that the practical application of microgrids heavily depends on local conditions, suggesting that Switzerland would benefit more from a consistent expansion of smart grids. Amongst other advantages, smart grids would also provide a useful foundation should the conditions in the future change in such a way that the implementation of microgrids becomes desirable.

[1] Definition by International Electrotechnical Commission (IEC, 2011): “Smart grid, electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as:
- to integrate the behaviour and actions of the network users and other stakeholders,
- to efficiently deliver sustainable, economic and secure electricity supplies”

[2] Definition by International Electrotechnical Commission (IEC, 2017): “Microgrid, <in an electric power system>: group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode”

# 1 Introduction

Microgrids are a popular concept in the electricity grid sector. They are described by some parties as an important piece of the puzzle for the grid of the future in Switzerland (e.g., BFE, 2015; Dammeier, 2015; Guibentif & Vuille, 2022). The following report therefore analyses the future role of microgrids in the Swiss electricity grid.

The terms microgrid and smart grid are often used as promising approaches in the discourse on the Swiss electricity grid of the future. Both describe concepts that are used and understood differently depending on the context. However, a precise understanding of the terms, including their advantages and disadvantages, is important for the successful and efficient development of the future Swiss electricity grid. Otherwise, misinterpretations and misunderstandings can lead to undesirable developments or pointless discussions.

## 1.1 Context

Following the pathway to full decarbonization, the Swiss energy system is undergoing far-reaching electrification of previously fossil-fuelled applications, in addition to the strong expansion of decentralised and intermittent renewable electricity generation. These developments require adjustments and additional infrastructure in the area of electricity grids. The design of the electricity grids in turn has a profound impact on the available options and the efficiency of the energy transition. In this context, this report discusses the role that microgrids could play at the level of Swiss municipalities today, and in the future.

## 1.2 Definitions

The International Electrotechnical Commission (IEC) defines *microgrids,* in line with the U.S. Department of Energy (Ton & Smith, 2012), as follows (IEC, 2017): "group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode". Two fundamental characteristics can be derived from this for a microgrid:

(a) operation in island mode requires the ability to be self-sufficient (without restrictions for the end user), at least for a certain period of time,

(b) operation in grid-connected mode requires the ability to synchronise with the grid.

Therefore, both an emergency generator (which cannot run synchronised with the grid and only supplies critical consumers) and a PV system without batteries (not capable to match demand in real-time at any given time) cannot be considered a microgrid. Importantly, a defining characteristic of a microgrid is not necessarily that it operates independently from an overarching grid, but that it can do so if needed.

The definition of a *smart grid* according to the IEC is as follows (IEC, 2011): “electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as:

- to integrate the behaviour and actions of the network users and other stakeholders,
- to efficiently deliver sustainable, economic, and secure electricity supplies”

The two concepts of microgrid and smart grid are not exclusive - a microgrid is usually also a smart grid, but it does not have to be. It is important to emphasise that by no means every smart grid is also a microgrid (see Figure 1). However, the two concepts can complement each other very well.

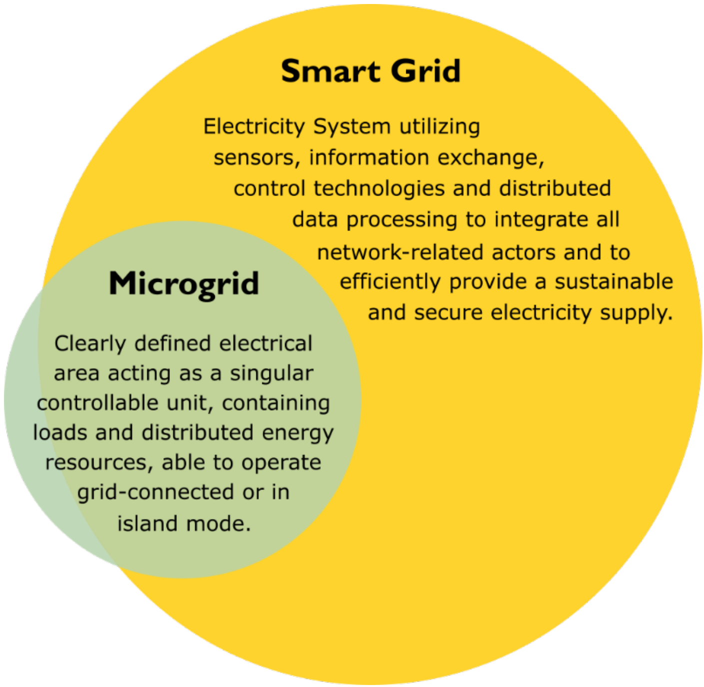


Figure 1. Venn diagram of the terms smart grid and microgrid. The term smart grid is much broader than the term microgrid. In most cases, microgrids are also smart grids. However, there are rare cases of microgrids that are not categorised as smart grids according to common definitions (e.g., International Electrotechnical Commission (IEC, 2017, IEC, 2011)). These are grids with a small number of controllable generators that very directly adjust the power they generate to supply all loads. In this case, the definition of interlinked loads and distributed energy resources may be fulfilled, while decisive criteria of a smart grid such as information exchange, control technologies and distributed data processing are not sufficiently fulfilled.

# 2 Microgrids in general

## 2.1 Types of microgrids

A distinction can be made between different types of microgrids that are optimised for local needs (Microgrids: The Way Forward, 2021).

- **Grid-connected microgrids** are normally connected to the transmission grid and collaborate with it. They can exchange energy with the overall grid and share storage capacity and other services such as ancillary services (frequency control, voltage support, etc.) with it. If there is a supply interruption in the overall grid, the microgrid can switch to island mode, i.e., disconnect from the grid and continue to supply its own end consumers without interruption.
- **Autonomous/isolated microgrids** are systems, which lie within the network area of the main power grid but do not have the technical installations to be connected to it. They have sufficient local generation to supply consumers and are thus independent of the main grid.
- **Remote microgrids** are far away from the overall grid, so a connection is not possible or economical. They are completely dependent on local generation.
- **Embedded microgrids** are normally private networks located behind a single connection point, usually in an urban environment. These are, for example, a campus, hospital, or shopping centre.

## 2.2 Advantages of microgrids

In the literature there are five central points that are repeatedly mentioned as motivation for the introduction of microgrids (Hirsch et al., 2018; Masrur et al., 2021; Ray & Biswal, 2020; Ton & Smith, 2012).

- Resilience: In the event of a blackout or brownout (voltage drop) of the superordinate grid, the microgrid is not immediately affected. This can be important in the event of a disaster or if the higher-level grid is regularly overloaded.
- Avoidance of transmission losses: A reduction in the required energy transmission distances leads to lower losses while maintaining the same line infrastructure. The increased generation of electricity directly in the same distribution grid as consumption reduces the transmitted energy, particularly in the higher grid levels.
- Fundamental shift towards locally produced renewable energy and self-sufficiency as well as local value creation and independence from fluctuating energy prices (better predictability). If a microgrid is implemented, generally there is increased coverage of consumption through local generation even in non-island operation (see chapter 2.3).
- Microgrids can act as a combined consumer or producer vis-à-vis the grid operator, if this is permitted by local legislation. They can reach a size that enables effective market participation - electricity can be purchased at more favourable conditions and sold at higher prices and ancillary services can be offered (example in chapter 2.3.5).
- Given that sensible regulations are in place, microgrids have a stabilising effect for the grid operator. Fluctuations from renewables are balanced out via a sub-grid and levelled out by local storage systems. Microgrids form a partially encapsulated sub-level that helps to integrate renewables into the electricity grid.

## 2.3 Examples of microgrids worldwide

The following loose collection of case studies is intended to illustrate some use cases of microgrids and the motivation to build them. A common feature of all the case studies found is that there are very specific conditions that speak in favour of implementing a microgrid.

<u>Bornholm, Denmark</u>
On the Danish island of Bornholm, the idea of setting up a microgrid was already being considered at the beginning of the 1980s, as it was foreseeable that local wind power would cover a large proportion of electricity consumption in the near future. The island is home to around 40,000 inhabitants and is connected to the Swedish grid via a 60 kV alternating current (AC) cable but can also be operated in

island mode. Through the EcoGrid EU project, the power grid on Bornholm was transformed into a "living laboratory" and demonstration project in which various new technologies could be demonstrated. The island is supplied by 16 MW combined heat and power (CHP) plants, 29 MW wind, 6.5 MW PV and 2 MW biogas, as well as 34 MW diesel and 25 MW oil-fired steam generators as backup. Demand-side management (DSM) trials have been carried out (Larsen et al., 2017; Ziras et al., 2019), several studies on the restructuring of the electricity market (Heinrich et al., 2020, 2021; Neska & Kowalska-Pyzalska, 2022; Pallesen & Jacobsen, 2018), V2G applications (Engelhardt et al., 2022; González-Garrido et al., 2019; Zecchino et al., 2019), as well as studies on more accurate forecasting and dispatchability of producers and consumers (Aslam et al., 2021; Huang et al., 2022; Larsen et al., 2017; Marinelli et al., 2021; Müller et al., 2022; Rasmussen et al., 2022). In addition, there are further studies on detailed technical issues and demonstration projects for specific technologies that have been carried out in Bornholm. Although the EU EcoGrid project has now been completed, results will continue to be published and the unique circumstances in Bornholm will be utilised for further studies.

Sunnyside Yard, New York City, USA

The "Sunnyside Yard" depot in Queens is located on the Long Island Railroad (LIRR) line ending at Penn Station, one of the most important railway stations in North America. After the storm Sandy in 2012, the depot had to rely on mobile emergency generators for over a month to maintain the power supply. At the same time, the track field in Sunnyside Yard is one of the last large "undeveloped" areas in New York. The combination of these factors resulted in the Sunnyside Yard Master Plan (Sunstainability & Green Infrastructure at Sunnyside Yard, 2019), which is currently still in the planning phase. A central element is the energy supply for both the new development and Penn Station, as well as the surrounding areas to a limited extent. In the final stage, a microgrid with an output of 17.2 MW and a battery capacity of 4 MWh is to be set up, consisting of a 6 MW CHP system, 2 natural gas generators, a 200 kW PV array and a zinc-air battery. The main motivation for this microgrid is the increased reliability because it could keep critical transportation services running during power outages (Wood, 2016).

Isle of Eigg, Scotland

The island of Eigg is part of the Scottish Hebrides and is not connected to the transmission grid. Until 2008, the island did not have its own grid either; instead, the approximately 100 inhabitants of the island each used their own generators. Under the leadership of the Heritage Trust, an electricity grid was set up on the island that is almost entirely fuelled by renewable energy. The system consists of a 54 kW PV array, three hydropower plants totalling 119 kW and a 24 kW wind farm, augmented with backup diesel generators (160 kW) (Chmiel & Bhattacharyya, 2015). Ultracaps, flywheels and batteries are used for storage.

Aspects of community energy in particular were highlighted at Eigg (Gormally et al., 2016; Lowitzsch et al., 2020; Martin, 2020; Melville et al., 2017; Warren & McFadyen, 2010), as the entire system is owned by the residents. Innovative solutions and rules have been created - for example, a self-imposed consumption limit of 5 kW for individual consumers and 10 kW for businesses. If this limit is exceeded, a penalty payment is due. There is also a traffic light system at the central pier: If the light is on red, residents should limit their electricity consumption; if it is green, one can consume normally (Gardiner, 2017). If too much electricity is produced, electric heaters are also switched on in communal areas (e.g. the church) in summer.

USMC Camp Pendleton, San Diego, USA

Since 2019, the US Marine Corps has been operating a microgrid consisting of a total of 150 kW PV systems and a 400 kWh redox flow battery at its Camp Pendleton base in San Diego (Burger, 2019). The focus here was clearly on the self-sufficiency of the system. The connection to the transmission grid is seen as a backup for critical infrastructure. The project is part of a larger strategy to become more independent in the energy sector and to simplify logistics (Reardon, 2012).

The University of California San Diego, San Diego, USA
On the San Diego campus of the University of California, a microgrid with a production capacity of 30 MW consists of a combined heat and power plant, 2.8 MW fuel cell, PV systems totalling 3 MW and a 2.5 MW battery (University of California, San Diego, 2020). A large heat storage system is also in use. The consumption is made up of the household consumption of students and employees who live on site, as well as the operation of teaching and research. As there is a healthcare facility, research laboratories and computer centres on the campus, 60 MW of diesel generators are available for emergencies.

The microgrid serves the University of California, which also conducts research in the energy sector, as a demonstration plant to gain experience in the operation of microgrids (Francklyn, 2018). It increases the resilience of the campus by ensuring the power supply for a certain period of time independently of the main grid in island mode. In addition, the microgrid is also the largest provider for the grid operator in the area of demand response in regular operation and can act as a backup for the normal power grid in the region in an emergency. In the past, this has come in very handy in the event of power outages due to forest fires.

## 2.4 Further developments

Low-voltage direct current microgrids
There are various reasons why an overwhelming majority of the electricity system is based on alternating current. The main reason is the simpler technology to transform the current to different voltage levels in AC systems. Traditionally, electricity generation was based on three-phase synchronous machines and consumers were usually able to use alternating current directly (three-phase machines, light bulbs, etc.). Today, there is a strong shift towards direct current (DC) generation: Firstly, via photovoltaics, which produces direct current, but wind turbines also usually have an intermediate DC stage. In addition, the technologies required to transform direct current are now fully developed (Law, 2022). On the consumer side, there is also an increasing shift towards direct current - a considerable proportion of modern electronic devices ultimately require direct current. Losses occur with every conversion in power converters, which could be avoided with direct current networks. In order to realise such concepts without having to completely replace larger grid areas, implementation in the microgrid sector, e.g. on an industrial site, can be a sensible option.

There is now a wealth of projects that demonstrate microgrids with a common DC bus and operation entirely without alternating current and associated conversions (Castillo-Calzadilla et al., 2022).

## 3 Microgrids in Switzerland

The following chapter analyses the known reasons and advantages for the expansion of microgrids in the Swiss context and provides an assessment of the role that microgrids could play in the Swiss energy system.

### 3.1 Conditions for microgrids in Switzerland

Switzerland has a dense electricity grid, which on the one hand covers the country very well and on the other hand creates redundancies by using meshed grids or at least open loops for the supply in many places. These guarantee that there is no interruption to the supply if there is a failure in one principal component of the power grid (meeting the N-1 contingency criterion). To establish such a redundancy, more than just the minimally required power lines need to be in place. Switzerland's high line density is reflected in a European comparison of line length per country area. Here, Switzerland has higher values than countries with a comparable population density meaning that even considering the population density, on relative terms, Switzerland features more power grid infrastructure (see Figure 2). This extra infrastructure can be used to increase redundancies or to provide increased network coverage. Both these factors are relevant for considerations of the role of microgrids because microgrids become less attractive alternatives when the main grid is more reliable and has a better coverage.

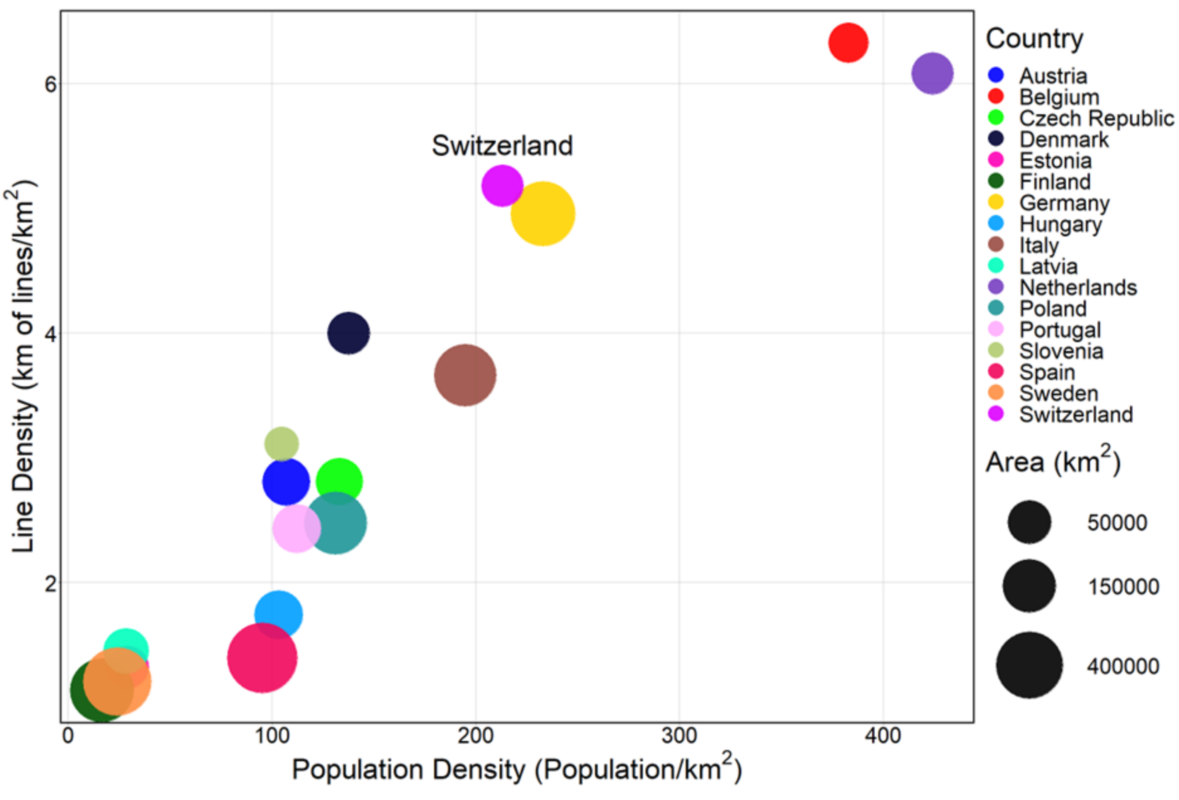


Figure 2. Line density in length (km) of cumulated transmission and distribution lines per land area (km$^2$) for selected European countries compared to their respective population densities. There is a positive correlation between population density and line density. Switzerland features a high line density both in absolute values and with respect to its population density. Source for the data on Switzerland is ElCom (ElCom, 2023b) and for compared European countries Eurelectric (Eurelectric, 2018).

In section 2.2, general advantages of microgrids were presented. In the following, these are specifically compared with the conditions in Switzerland and the extent to which they apply here is analysed.

Resilience

The Swiss electricity grid is currently very reliable and major blackouts are extremely rare. Short-term power outages are conceivable after natural disasters, but Switzerland is still well positioned here. The System Average Interruption Duration Index (SAIDI) is the average duration of the interruption of an electricity grid per consumer supplied per year. For years, Switzerland has had excellent values in this index in the range of 15 to 25 minutes (see Figure 3). The Swiss electricity grid is therefore in this regard one of the best if not the best in Europe.

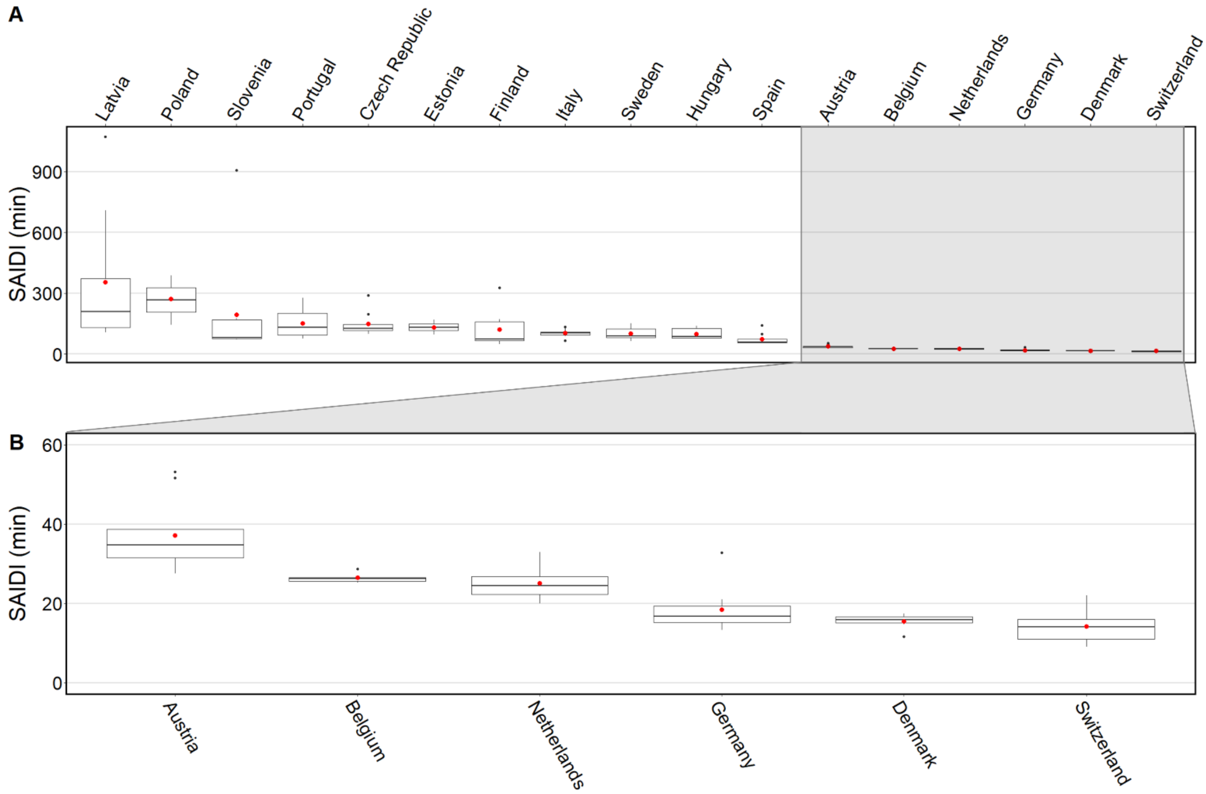


Figure 3. **A**: Comparison of System Average Interruption Duration Index (SAIDI) given in minutes in selected European countries with Switzerland. Shown values are from years 2010 to 2018. Red dots display the average of the values in the boxplots. Switzerland had the lowest average and median of the hereby compared countries for the given time period. Source for the data on Switzerland is ElCom (ElCom, 2023a) and for compared European countries the Council of European Energy Regulators (CEER, 2022).
**B**: Zoomed boxplot of the six countries with the best SAIDI values.

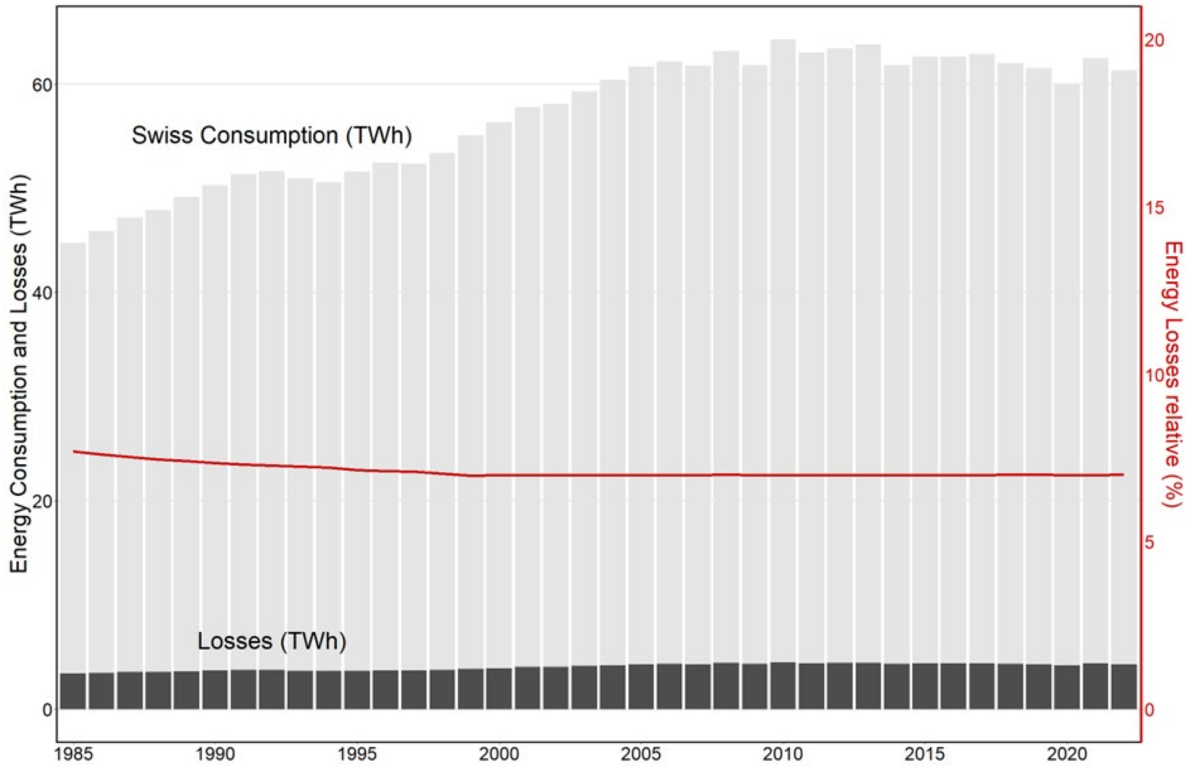


Figure 4. Evolution of yearly total electricity consumption of Switzerland (light gray) and associated losses (dark gray). The red line indicates the fraction of electric energy lost between generation and consumption, which includes (but not exclusively) losses in transmission and distribution lines. These losses are at a very stable level of around 7 %. Data originate from the Swiss Federal Office of Energy (SFOE, 2023).

Avoidance of transmission losses

Avoiding transmission losses is a small potential lever in Switzerland, as losses are in the mid single-digit percentage range at around 7 % (see Figure 4). The Swiss electricity grid also ranks very well in terms of losses in an international comparison (CEER, 2022), which is a further indication that the potential for optimisation is low.

Only a portion of the total reported losses could be avoided by microgrid solutions. The proportion of losses occurring in the transmission grid is not explicitly stated, but it is known that the majority occur in grid levels 5 and 7 (Bundesrat, 2022), as these are significantly more extensive and have lower voltage levels. It should be noted that the use of microgrids could mainly avoid the transmission of energy and thus losses at the higher grid levels due to the increased self-sufficiency at the lowest voltage level. However, the exchange of energy in the low-voltage grid, where a large proportion of the losses occur due to the low voltage, would still be necessary within microgrids.

Fundamental shift towards locally produced renewable energy and self-sufficiency

The transition to an energy system with decentralised, renewable power generation is a megatrend. This is accompanied by endeavours to achieve local energy self-sufficiency, which also has a political dimension. In this context, microgrids can increase local value creation and communities can become less dependent on fluctuating energy prices. In 2019, Switzerland with its federalist institutions had 610 distribution system operators (ElCom, 2023b), which also act as energy providers (no unbundling like in other European countries). Switzerland thus has a very high number of energy providers compared to its size and population resulting in many communities being supplied by small local utilities. While it is difficult to objectively evaluate, how strong this advantage of microgrids would need to be rated in the

Swiss context, it is to be expected that the argument is weaker in comparison to many other countries with more centralized utilities (Eurelectric, 2018).

Market participation and transactive energy system

Establishing a microgrid as a means to improve market participation by acting as a single entity with a higher consumption and production is not assumed to be a strong motivation in Switzerland. There are options to achieve many of these goals with considerably smaller efforts. Swiss legislation already allows producers and consumers to cooperate and act as a single entity in their business relation with the local distribution system operator (DSO). These local electricity communities ("Lokale Elektrizitätsgemeinschaften, LEG") enable self-consumption of decentrally produced electricity among actors that are in the same distribution grid and even allow the usage of powerlines from DSOs.

Stabilising effect on the network

The stabilising effect or containment of the fluctuations of new renewable energies is dependent on the specific setup and degree of expansion of the microgrid. Quantifying the added economic value resulting from the elimination of grid expansions and less use of balancing energy or dynamically controllable generators would need to be done on a case-by-case basis.

## 3.2 Role of microgrids in the Swiss energy system

Switzerland already has a very well-developed electricity grid infrastructure as shown in chapter 3.1 and as reflected by top positions in international rankings such as for example by the World Economic Forum (WEF, 2017). The application of microgrids would therefore generally take place in existing grid areas that function well under current conditions. Equipping existing distribution grids with the infrastructure for microgrid capability currently involves substantial additional costs and operating a microgrid close to a self-sufficient operating point is generally more inefficient. In addition to the grid-side components and advanced control algorithms, the necessary generation and storage capacities must also be created so that the microgrid can be operated in island mode for as long as desired. This involves implementing on a small scale what already works in the existing Swiss electricity grid. The relative demand per connection for generation, storage and demand-side management increases the smaller the self-sufficient electricity grid is to be, because there is less natural balancing due to different consumption and generation profiles as the number of connected agents decreases, and because the simultaneity of production or demand also has a spatial component. A rollout of microgrids therefore incurs substantial costs. These must be offset against the benefits generated by the microgrid capability in order to make a well-founded implementation decision.

Table 1. Comparison of microgrids and smart grids in terms of their benefits described in chapter 2.2. Most advantages of microgrids can be achieved by establishing advanced microgrids. The key difference is the microgrids' ability to run in island-mode in case of outages in the general power grid. However, smart grids already improve the resilience of grids with their improved transparency of the grid status and mechanisms to adapt the power of actors proactively.

| Advantages | Smart Grid | Microgrid |
|---|---|---|
| Resilience | (x) | x |
| Avoidance of transmission losses | x | x |
| Locally produced renewable energy | x | x |
| Combined user/producer vis-à-vis DSO | (x) | x |
| Stabilising effect for network | x | x |

The role of microgrids in an energy system depends on the specific local conditions. In Switzerland, many of the actual advantages of microgrids do not materialise on a large scale due to the very well-developed electricity grid. Moreover, most of the advantages of microgrids can already be achieved with advanced smart grids, which can be realised at a lower cost. Figure 5 contains a schematic comparison of the costs and benefits of microgrids with smart grids, while Table 1 provides a comparison of the two approaches.

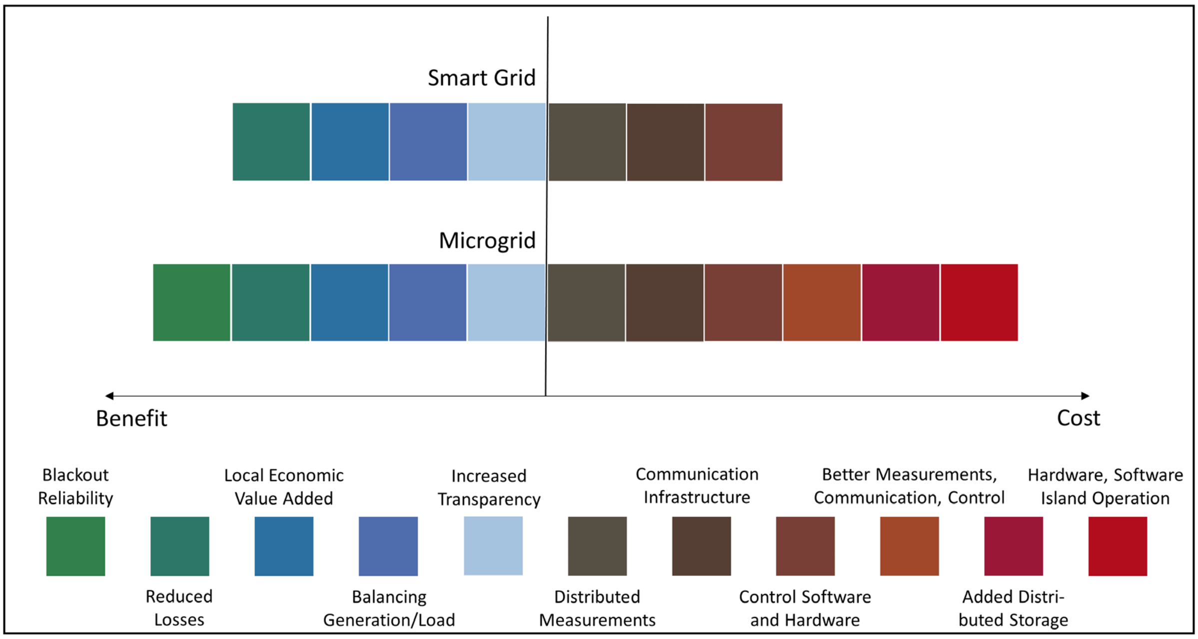


Figure 5. Conceptual illustration of the cost-benefit ratio in comparison between smart grids and microgrids for standard grid situations in Switzerland. The uniform blocks are placeholders for costs and benefits, which are going to differ substantially by specific project, so their same size here does not mean that they represent equal amounts. The benefits of smart grids and microgrids are largely the same, with the main difference being the reliability of microgrids in the event of blackouts of the interconnected system, while the costs for microgrids are estimated to be significantly higher. On the one hand, key requirements such as distributed metering infrastructure, communication infrastructure and the control software and hardware must be more robust and comprehensive, and on the other hand, new cost components such as distributed storage and the hardware and software for island operation must be added. The visualisation refers to typical distribution grids in Switzerland with already expanded distributed generation and smaller (home) storage systems. Because electricity grids are infrastructure adapted to local conditions, the actual costs vary from case to case.

## 4 Conclusion

Microgrids are a popular research topic, which is illustrated by the active research landscape. Many publications focus on the technical solution of an assumed goal of local self-sufficiency, for which microgrids are predestined. The question of the role of microgrids in the future electricity grid must be answered on a location-specific basis, as both the costs and the benefits of microgrids can vary greatly depending on local conditions. It is therefore important to consider the context and the challenges to be solved in the real system of the specific country when making implementation recommendations based on research projects.

Main reasons for the high level of interest in microgrids could be the constantly improving availability of technical solutions for energy storage (e.g. cheaper batteries) and decentralised power supply (e.g. cheaper PV panels), as well as the spreading use of smart grid technologies. In the past, microgrids were often realised in locations where the conditions for a standard grid connection were not optimal or where research interests in the field of microgrids existed. In the future, the availability and cost-effectiveness of storage systems, generators, and flexible consumers will continue to improve, while the conditions could develop in a direction favourable to microgrids. Increased energy consumption for economic development, electrification for decarbonisation, climate and natural disaster resilience, fluctuating energy prices, trends towards de-globalisation, and the feed-in of large amounts of renewable energy are likely to combine to expand the application possibilities of microgrids worldwide.

The case of Switzerland, however, does not prove to be one with favourable conditions for the use of microgrids. Switzerland has a dense electricity grid that covers the country very well, high quality setups, and largely meshed grids, which leads to very low outages and losses, and (pumped) hydro storage power plants in the Alps for balancing. This means that the conditions for the use of microgrids are unfavourable because directly connecting to the general electricity grid is more efficient in economic and technical terms. It can be assumed that the use of microgrids will expand worldwide, while in Switzerland the conditions are only favourable in individual cases for microgrids to be able to exploit their advantages. Given that the reliability of the Swiss electricity grid remains very high, we therefore assume that microgrids will not play a significant role in the Swiss electricity grid of the future in the medium term. This assessment may change depending on future developments. In particular, the increase in resilience through the use of microgrids should be mentioned here. The power of this advantage depends on the interplay between the reliability of the public electricity grid, the level of damage in the event of an outage, and the costs of creating a microgrid. If the reliability of the Swiss electricity grid decreases in the future in conjunction with falling costs for microgrids, conditions could be reached, where the construction of microgrids becomes sensible. Particularly the costs of microgrids are in the process of being significantly reduced. Reasons are the large-scale expansion of decentralised generation and decentralised storage as part of the energy transition, while research and rollouts of active distribution grids are reducing the additional hardware and software systems required for the autonomous operation of microgrids.

This contrasts with smart grids, which are an umbrella term for various forward-looking measures in the electricity grid. The coordinated, optimised operation of electricity grids promises gains in efficiency and reliability, enables better integration of fluctuating renewable generation into the electricity grid, better opportunities for participation, and is fuelled by the two global megatrends of digitalisation and sustainability. The key difference between a microgrid and a smart grid with a high degree of local self-sufficiency is the technical requirement that the grid section can also be operated in island-mode (see official definitions). The measures to locally coordinate consumption and generation can be implemented with smart grid measures and are independent of the technical requirements for temporary island operation. The ability to operate in island mode generates additional costs and complexities, while the added value is currently modest in typical Swiss grids. One exception is critical infrastructure that requires continuous power.

The creation of microgrids with the reasoning that higher grid levels will have to compensate for fewer fluctuations is a question of the system boundaries under consideration: At the level of the overall system, if you aggregate all infrastructure for generation, loads, grids, and storage, both from the interconnected grid and underlying microgrids, the need for systems and technical solutions for power balancing increases in many cases with greater use of microgrids. Only when considering the interconnected grid alone, without the underlying microgrids, does the effort for power balancing decrease due to the creation of microgrids. However, these are outsourced to the microgrids to an even greater extent because balancing profits less from naturally differing generation and load patterns, which increase with higher number of actors and a bigger spatial extent. Exceptions are insufficient grid capacities between voltage levels and/or differing locations. Microgrids make sense in this context if self-sufficiency offers great added value due to increased resilience or if their use can save on grid expansions to a greater extent than the additional infrastructure required for the microgrid. As long as the power grids at the higher grid levels are not overloaded, centralised measures and balancing solutions will generally be cheaper than greater local self-sufficiency due to economies of scale and the use of locational advantages.

# 5 References


Aslam, S., Herodotou, H., Mohsin, S. M., Javaid, N., Ashraf, N., & Aslam, S. (2021). A survey on deep learning methods for power load and renewable energy forecasting in smart microgrids. *Renewable and Sustainable Energy Reviews*, *144*, 110992. https://doi.org/10.1016/j.rser.2021.110992

BFE. (2015). *Smart Grid Roadmap Schweiz—Wege in die Zukunft der Schweizer Elektrizitätsnetze* (p. 39). Bundesamt für Energie, BFE. https://www.newsd.admin.ch/newsd/message/attachments/38814.pdf

Bundesrat. (2022). *Welches Potenzial liegt in der Dekarbonisierung der Stromübertragungs- und -verteilnetze?* Schweizer Bundesrat. https://www.parlament.ch/de/ratsbetrieb/suche-curia-vista/geschaeft?AffairId=20223785

Burger, A. (2019, May 13). New Microgrid Now Operating in Camp Pendleton, San Diego, California. *Microgrid Knowledge*. https://www.microgridknowledge.com/microgrids/military/article/11429715/new-microgrid-now-operating-at-camp-pendleton-in-san-diego-california

Castillo-Calzadilla, T., Cuesta, M. A., Olivares-Rodriguez, C., Macarulla, A. M., Legarda, J., & Borges, C. E. (2022). Is it feasible a massive deployment of low voltage direct current microgrids renewable-based? A technical and social sight. *Renewable and Sustainable Energy Reviews*, *161*, 112198. https://doi.org/10.1016/j.rser.2022.112198

CEER. (2022). *7th CEER-ECRB Benchmarking Report on the Quality of Electricity and Gas Supply*. Council of European Energy Regulators, CEER. https://www.ceer.eu/documents/104400/7324389/7th+Benchmarking+Report/15277cb7-3ffe-8498-99bb-6f083e3ceecb

Chmiel, Z., & Bhattacharyya, S. C. (2015). Analysis of off-grid electricity system at Isle of Eigg (Scotland): Lessons for developing countries. *Renewable Energy*, *81*, 578–588. https://doi.org/10.1016/j.renene.2015.03.061

Dammeier, F. (2015). *Integration erneuerbarer Energiequellen in das Schweizer Verteilnetz: Möglichkeiten von Microgrids*. ZHAW. https://doi.org/10.21256/zhaw-1058

ElCom. (2023a). *Stromversorgungsqualität 2022*. Eidgenössische Elektrizitätskommission, ElCom. https://www.elcom.admin.ch/dam/elcom/de/dokumente/2023/stromversorgungsqualitaet2022.pdf.download.pdf/Stromversorgungsqualit%C3%A4t.pdf

ElCom. (2023b). *Tätigkeitsbericht der ElCom 2022*. Eidgenössische Elektrizitätskommission ElCom. https://www.elcom.admin.ch/dam/elcom/de/dokumente/2023/taetigkeitsbericht-elcom-2022.pdf.download.pdf/Taetigkeitsbericht_ElCom_2022-DE.pdf

Engelhardt, J., Zepter, J. M., Gabderakhmanova, T., & Marinelli, M. (2022). Energy management of a multi-battery system for renewable-based high power EV charging. *eTransportation*, *14*, 100198. https://doi.org/10.1016/j.etran.2022.100198

Eurelectric. (2018). *Power Distribution in Europe—Facts & Figures*. Union of the Electricity Industry - EURELECTRIC. https://cdn.eurelectric.org/media/1835/dso_report-web_final-2013-030-0764-01-e-h-D66B0486.pdf?_gl=1*txqqtv*_ga*MTczNDA1OTkyNy4xNzA5NTk3NzE1*_ga_CB82F90MQ6*MTcxMjEwMzMxMS4yLjEuMTcxMjEwMzMzMC40MS4wLjA.

Francklyn, L. (2018, November 13). Inside the World's Most Advanced Microgrid: The University of California San Diego. *Homer Microgrid News*. https://microgridnews.com/inside-the-worlds-most-advanced-microgrid-university-of-california-san-diego/

Gardiner, K. (2017). The small Scottish isle leading the world in electricity. *BBC*. https://www.bbc.com/future/article/20170329-the-extraordinary-electricity-of-the-scottish-island-of-eigg

González-Garrido, A., Thingvad, A., Gaztañaga, H., & Marinelli, M. (2019). Full-scale electric vehicles penetration in the Danish Island of Bornholm—Optimal scheduling and battery degradation under driving constraints. *Journal of Energy Storage*, *23*, 381–391. https://doi.org/10.1016/j.est.2019.03.025

Gormally, A. M., Whyatt, J. D., Timmis, R. J., & Pooley, C. G. (2016). Renewable energy scenarios: Exploring technology, acceptance and climate – Options at the community-scale. *Applied Geography*, *74*, 73–83. https://doi.org/10.1016/j.apgeog.2016.06.013

Guibentif, T. M. M., & Vuille, F. (2022). Prospects and barriers for microgrids in Switzerland. *Energy Strategy Reviews*, *39*, 100776. https://doi.org/10.1016/j.esr.2021.100776

Heinrich, C., Ziras, C., Jensen, T. V., Bindner, H. W., & Kazempour, J. (2021). A local flexibility market mechanism with capacity limitation services. *Energy Policy*, *156*, 112335. https://doi.org/10.1016/j.enpol.2021.112335

Heinrich, C., Ziras, C., Syrri, A. L. A., & Bindner, H. W. (2020). EcoGrid 2.0: A large-scale field trial of a local flexibility market. *Applied Energy*, *261*, 114399. https://doi.org/10.1016/j.apenergy.2019.114399

Hirsch, A., Parag, Y., & Guerrero, J. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews*, *90*, 402–411. https://doi.org/10.1016/j.rser.2018.03.040

Huang, C., Zong, Y., You, S., & Træholt, C. (2022). Economic model predictive control for multi-energy system considering hydrogen-thermal-electric dynamics and waste heat recovery of MW-level alkaline electrolyzer. *Energy Conversion and Management*, *265*, 115697. https://doi.org/10.1016/j.enconman.2022.115697

IEC. (2011). Smart Grid. In *Electropedia*. International Electrotechnical Commission, IEC. https://www.electropedia.org/iev/iev.nsf/display?openform&ievref=617-04-22

IEC. (2017). Microgrid. In *Electropedia*. International Electrotechnical Commission, IEC. https://www.electropedia.org/iev/iev.nsf/display?openform&ievref=617-04-22

Larsen, E. M., Pinson, P., Leimgruber, F., & Judex, F. (2017). Demand response evaluation and forecasting—Methods and results from the EcoGrid EU experiment. *Sustainable Energy, Grids and Networks*, *10*, 75–83. https://doi.org/10.1016/j.segan.2017.03.001

Law, E. (2022, December 20). *Can We Eliminate These 3 Types of Line Losses in Transmission Systems?* https://www.cencepower.com/blog-posts/line-losses-power-transmission-3-types

Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J. (2020). Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future? *Renewable and Sustainable Energy Reviews*, *122*, 109489. https://doi.org/10.1016/j.rser.2019.109489

Marinelli, M., Sevdari, K., Calearo, L., Thingvad, A., & Ziras, C. (2021). Frequency stability with converter-connected resources delivering fast frequency control. *Electric Power Systems Research*, *200*, 107473. https://doi.org/10.1016/j.epsr.2021.107473

Martin, R. (2020). Making sense of renewable energy: Practical knowledge, sensory feedback and household understandings in a Scottish island microgrid. *Energy Research & Social Science*, *66*, 101501. https://doi.org/10.1016/j.erss.2020.101501

Masrur, H., Sharifi, A., Islam, Md. R., Hossain, Md. A., & Senjyu, T. (2021). Optimal and economic operation of microgrids to leverage resilience benefits during grid outages. *International Journal of Electrical Power & Energy Systems*, *132*, 107137. https://doi.org/10.1016/j.ijepes.2021.107137

Melville, E., Christie, I., Burningham, K., Way, C., & Hampshire, P. (2017). The electric commons: A qualitative study of community accountability. *Energy Policy*, *106*, 12–21. https://doi.org/10.1016/j.enpol.2017.03.035

*Microgrids: The Way Forward*. (2021). International Microgrid Association.

Müller, N., Chevalier, S., Heinrich, C., Heussen, K., & Ziras, C. (2022). Uncertainty quantification in LV state estimation under high shares of flexible resources. *Electric Power Systems Research*, *212*, 108479. https://doi.org/10.1016/j.epsr.2022.108479

Neska, E., & Kowalska-Pyzalska, A. (2022). Conceptual design of energy market topologies for communities and their practical applications in EU: A comparison of three case studies. *Renewable and Sustainable Energy Reviews*, *169*, 112921. https://doi.org/10.1016/j.rser.2022.112921

Pallesen, T., & Jacobsen, P. H. (2018). Solving infrastructural concerns through a market reorganization: A case study of a Danish smart grid demonstration. *Energy Research & Social Science*, *41*, 80–88. https://doi.org/10.1016/j.erss.2018.04.005

Rasmussen, T. B. H., Wu, Q., & Zhang, M. (2022). Combined static and dynamic dispatch of integrated electricity and heat system: A real-time closed-loop demonstration. *International Journal of Electrical Power & Energy Systems*, *143*, 107964. https://doi.org/10.1016/j.ijepes.2022.107964

Ray, P., & Biswal, M. (Eds.). (2020). *Microgrid: Operation, Control, Monitoring and Protection* (Vol. 625). Springer Singapore. https://doi.org/10.1007/978-981-15-1781-5

Reardon, S. (2012). Eco-warriors: US military pushes for green energy. *New Scientist*, *216*(2889), 6–8. https://doi.org/10.1016/S0262-4079(12)62796-1

SFOE. (2023). *Schweizerische Gesamtenergiestatistik 2022*. Swiss Federal Office of Energy, SFOE. https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTE0NTQ=.html

*Sunstainability & Green Infrastructure at Sunnyside Yard*. (2019). NYCEDC & AMTRAK.

Ton, D. T., & Smith, M. A. (2012). The U.S. Department of Energy's Microgrid Initiative. *The Electricity Journal*, *25*(8), 84–94. https://doi.org/10.1016/j.tej.2012.09.013

University of California, San Diego. (2020). *University of California San Diego Microgrid*. https://chptap.ornl.gov/profile/356/UCSDMicrogrid-Project_Profile.pdf

Warren, C. R., & McFadyen, M. (2010). Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. *Land Use Policy*, *27*(2), 204–213. https://doi.org/10.1016/j.landusepol.2008.12.010

WEF. (2017). *Global Energy Architecture Performance Index Report 2017*. World Economic Forum, WEF. https://www3.weforum.org/docs/WEF_Energy_Architecture_Performance_Index_2017.pdf

Wood, E. (2016, August 23). Amtrak Arrives in Microgrid Era Ahead of Schedule. *Microgrid Knowledge*. https://www.microgridknowledge.com/google-news-feed/article/11432158/amtrak-arrives-in-microgrid-era-ahead-of-schedule

Zecchino, A., Prostejovsky, A. M., Ziras, C., & Marinelli, M. (2019). Large-scale provision of frequency control via V2G: The Bornholm power system case. *Electric Power Systems Research*, *170*, 25–34. https://doi.org/10.1016/j.epsr.2018.12.027

Ziras, C., Heinrich, C., Pertl, M., & Bindner, H. W. (2019). Experimental flexibility identification of aggregated residential thermal loads using behind-the-meter data. *Applied Energy*, *242*, 1407–1421. https://doi.org/10.1016/j.apenergy.2019.03.156