What role do community microgrids play in increasing energy efficiency and resilience in a decentralized energy infrastructure?

CARINA WAGNER, PETR MASTNY
Fakulta elektrotechniky a komunikačních technologií
Brno University of Technology,
Antonínská 548/1, 602 00 Brno
CZECH REPUBLIC

Abstract: - The role of community microgrids in enhancing energy efficiency and resilience within a decentralized energy infrastructure has gained significant importance in re-cent years. In light of the challenges posed by an increasingly overburdened centralized energy supply and the globally rising demands for sustainability, resilience, and grid stability, community microgrids offer a forward-looking solution. They enable local, decentralized energy supply by integrating renewable energy sources such as solar and wind power, alongside advanced storage systems optimized by intelligent control technologies. These microgrids not only contribute to increased energy efficiency by minimizing transmission losses and maximizing self-consumption but also improve the resilience of local infrastructure by reducing dependence on centralized power grids and enhancing the ability to recover quickly from disruptions and emergencies, such as nat-ural disasters. This article examines the role of community microgrids as central components of a modern, decentralized energy infrastructure and explores the various challenges and opportunities related to their development, implementation, and scaling. Finally, it provides an outlook on future developments and highlights the need for political and technological support to further expand community microgrids on a global scale.

Key-Words: - Community Microgrid, Decentralized Energy Infrastructure, Grid Stability, Renewable Energy

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1 Introduction

The global energy infrastructure has evolved over the past decades from a centralized model based on large power plants and extensive transmission networks to a more decentralized, flexible, and sustainable structure. This transformation has been driven primarily by the shift to renewable energy sources, increasing demands for grid stability, and the growing pressure for sustainable and resilient solutions. Particularly in remote rural areas or urban neighborhoods seeking greater self-sufficiency, Com-munity Microgrids offer an attractive solution. They enable local communities to manage their energy supply independently, thus fostering not only local energy autonomy but also reducing CO_2 emissions and enhancing resilience against external disruptions.

At the heart of Community Microgrids lies the concept of combining decentralized energy supply with a variety of technologies to create an efficient, sustainable, and resilient energy infrastructure. This is achieved by integrating renewable energy sources (such as solar and wind power) with smart storage systems and innovative control technologies that manage and optimize energy flows. Furthermore, Microgrids are capable of operating autonomously during central grid disruptions, providing increased resilience. The potential benefits of Community Microgrids range from reducing transmission losses and energy supply bottlenecks to creating new jobs and promoting social equity.

2 Concept and Functionality of Community Microgrids

A Community Microgrid is a small, localized, and autonomous energy system designed to provide electricity to a community or region. It combines various technologies to generate, store, and distribute energy according to local needs. Energy production takes place on-site, while consumers within the community are interconnected. This structure enables an efficient and sustainable energy supply tailored to the specific requirements of the local community.

At the core of a Community Microgrid are renewable energy sources such as solar panels, wind turbines, or biogas plants. These locally available sources produce clean, low-carbon energy, reducing reliance on fossil fuels and helping to lower greenhouse gas emissions. However, since renewable energy production often depends on weather conditions and can fluctuate, energy storage integration plays a critical role. Battery storage systems, such as lithium-ion batteries, and thermal storage solutions al-low excess energy generated during periods of high production to be stored and used during times of low production or high demand. This stabilizes the energy supply and compensates for the intermittent nature of renewable energy sources.

Another essential component of a Community Microgrid is intelligent control systems. These systems monitor energy generation, consumption, and storage levels in real time. They optimize energy distribution to ensure efficient utilization and dynamically adjust consumption to match the available energy. These systems are support-ed by advanced communication networks that enable data exchange between the various components. Smart meters and sensors continuously collect information about energy flows, ensuring that they can be managed efficiently and in line with demand. In Germany, the expansion of such infrastructure is strictly regulated to ensure safety standards and protect against manipulation or cyberattacks. Science and legislation actively drive the development and standardization of norms and protocols in this field.

A Community Microgrid can operate in two modes: grid-connected and island mode. In grid-connected mode, the microgrid is connected to the central power grid. In this configuration, excess energy produced locally can be fed into the central grid, or energy can be drawn from it when needed. In island mode, the microgrid operates entirely autonomously, ensuring the local community's energy supply even during central grid outages. This flexibility makes Community Microgrids a promising solution for sustainable, resilient, and decentralized energy systems.

2.1 Energy Efficiency Through Community Microgrids

Community Microgrids play a significant role in enhancing energy efficiency by minimizing energy losses, optimizing consumption, and integrating advanced energy management systems. Traditional centralized energy systems often involve substantial energy losses during the transmission and distribution of electricity over long distances. By contrast, Community Microgrids generate energy locally, significantly reducing these transmission losses and increasing overall system efficiency.

One of the key factors contributing to energy efficiency in Community Microgrids is the ability to maximize self-consumption of locally generated renewable energy. Instead of relying on centralized grids, communities can use energy produced on-site from sources such as solar panels or wind turbines. This reduces dependency on external energy supplies and ensures that the energy produced is consumed where it is needed most.

Energy storage systems further improve efficiency by storing excess energy during periods of high production and discharging it during peak demand or low production periods. This minimizes the need to draw energy from the central grid, reduces wastage, and allows for more consistent energy availability. Battery storage, combined with demand-side management techniques, helps to flatten demand peaks and balance supply with consumption, ensuring that energy is used in the most efficient way possible.

Intelligent energy management systems and smart grid technologies are another cornerstone of energy efficiency in Community Microgrids. These systems use advanced algorithms to monitor, predict, and optimize energy flows in real time. For instance, they can prioritize energy consumption for essential services, manage battery charging and discharging, or schedule energy-intensive tasks during times of surplus production. By leveraging data from smart meters and sensors, these systems ensure that energy is allocated and used optimally within the community.

Additionally, Community Microgrids encourage energy-conscious behavior among consumers. With greater transparency and access to real-time data about energy generation and consumption, individuals and businesses are more likely to adopt energy-saving practices. This not only contributes to energy efficiency but also pro-motes a culture of sustainability within the community.

In summary, Community Microgrids improve energy efficiency by localizing energy production, reducing transmission losses, maximizing renewable energy use, integrating energy storage, and employing advanced management systems. These benefits make them a pivotal element in achieving a more efficient and sustainable energy future.

2.2 Enhancing Resilience and Grid Stability Through Community Microgrids

Community Microgrids are not only efficient but also highly resilient to external disruptions. They play a vital role in improving grid stability and the resilience of energy systems, especially in regions that are prone to natural disasters or frequent grid failures. These regions are often located at the edges of grid networks or in countries where large-scale centralized grids have not been fully developed.

Island Mode: In island mode, Community Microgrids can operate completely independently from central power grids. This is particularly advantageous during crisis situations, as they can continue to supply power even if the central grid fails. This capability ensures continuity of power supply and enhances the safety and security of local communities.

Flexibility in External Disturbances: Due to their decentralized structure and use of local energy sources, Community Microgrids are less vulnerable to widespread outages or disturbances. If one component fails, the overall system is not significantly affected, as other units can continue providing energy.

Rapid Recovery: After a disruption, Community Microgrids can be reactivated much faster than centralized energy systems. This is due to the local control and the ability to selectively restore operations of individual components, without relying on com-plex transmission networks.

2.3 Economic and Social Dimensions of Community Microgrids

Community Microgrids not only offer technical and environmental benefits but also have significant economic and social impacts. The ability to generate and store energy locally reduces dependence on expensive centralized power sources, leading to cost savings. Over time, communities can substantially lower their energy costs by optimizing self-consumption and utilizing renewable energy sources.

Furthermore, Community Microgrids empower local communities to control their energy supply independently. This is especially important in rural areas, where they can provide access to reliable, affordable, and clean energy. The implementation of Community Microgrids can also raise awareness of renewable energy and sustainable practices, fostering a culture of environmental responsibility within these communities.

2.4 Challenges in the Implementation of Community Microgrids

The development and implementation of Community Microgrids, however, come with several challenges that need to be addressed:

- **Legal and Regulatory Frameworks**

The legal and regulatory frameworks for microgrids vary significantly across different regions and countries. These variations can complicate the implementation and scaling of microgrid projects, as local regulations may impose specific requirements or restrictions that need to be navigated.

- **High Initial Investment**

Establishing microgrids requires substantial investments in infrastructure, technology, and expertise. Although long-term savings can be significant, the high upfront costs often present a barrier to adoption, especially in regions with limited financial re-sources.

- **Integration of Renewable Energy Sources and Advanced Technologies**

The integration of various renewable energy sources, storage solutions, and intelligent control systems demands advanced technologies and specialized knowledge. Ensuring interoperability between different components of the system remains a challenge, as it requires seamless coordination and compatibility across a variety of technologies and manufacturers.

3 Comparsion of Energy Autonomy in Different Systems – Single Family House

3.1 Existing Buildings (Brownfield)

Table 1 “Brownfield”-Parameter System 1(160 qm²) and System 2 (130 qm²)

size single family house	160 qm ²	130 qm ²
electricity consumption	4800 kWh	3000 kWh
gas consumption	21000 kWh	18000 kWh
PV panel	0 kWp	10 kWp
Battery	0 kWp	15 kWp

3.1.1 Single Family House with non Renewable Energy

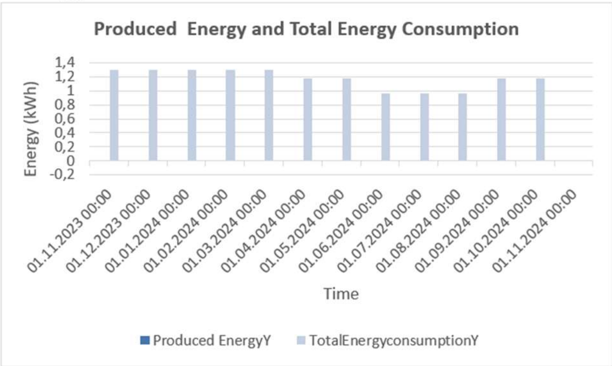

Figure 1
"Brownfield" Total Energy Consumption System 1 (160 qm²)

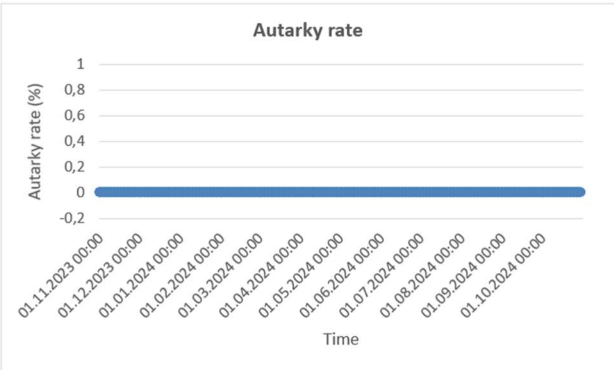

Figure 2
"Brownfield" Autarky Rate System 1 (160 qm²)

The analyzed system exhibits significant weaknesses in energy supply. It is particularly noticeable that no energy is being generated by a photovoltaic (PV) system, which keeps both the autonomy and self-consumption rates at a constant 0%. As a result, the system is entirely dependent on external energy sources, which not only leads to higher operating costs but also increases vulnerability to price fluctuations and supply shortages. Possible reasons for the lack of PV production could include the absence of an installed system, technical failures, or seasonal factors such as low sunlight.

The energy consumption of the system shows fluctuations between 0.252 kWh and 1.300 kWh, with a median of 0.807 kWh. This indicates a stable base load, supplemented by peak loads that occur due to intensive use of specific devices. The constant base load is likely caused by continuous consumers such as heating or cooling systems. Although this consumption is predictable, the lack of self-production amplifies the dependence on external sources.

An improvement to the system could be achieved by installing a PV system. A properly sized PV system would allow at least part of the energy demand to be covered by renewable energy, reducing dependence on external sources. Additionally, a battery storage system could store excess energy and provide it during periods of low production, such as at night or on cloudy days. This would significantly increase both autonomy and self-consumption rates, while also improving supply security.

In its current form, the system is neither sustainable nor future-proof. However, it has great potential to be transformed into a modern and independent energy infrastructure through the use of PV systems, battery storage, and consumption optimizations. Such measures would not only lower operating costs but also reduce environmental impact and enhance long-term supply security.

3.1.2 Single Family House with Renewable Energy (PV, Battery Storage)

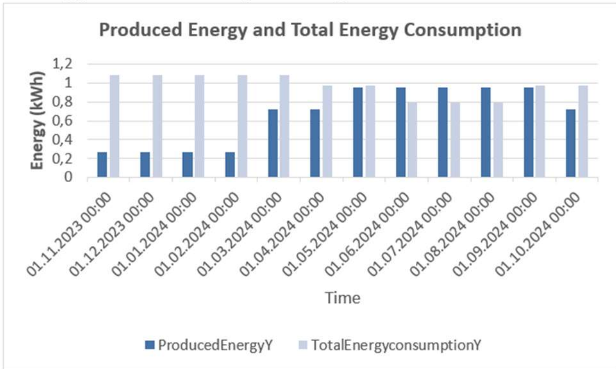

Figure 3
"Brownfield" Total Energy Consumption System 2 (130 qm²)

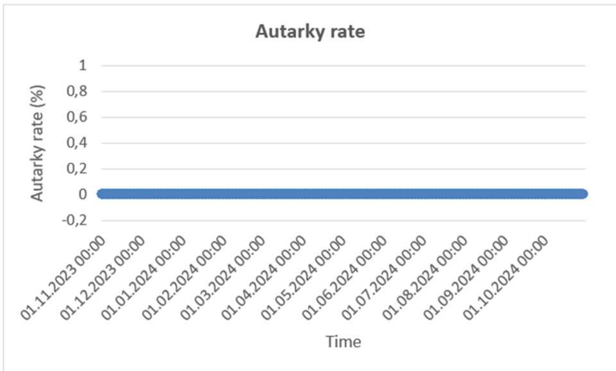

Figure 4
"Brownfield" Autarky Rate System 2 (130 qm²)

The analyzed system exhibits significant deficiencies in energy supply. Notably, no energy is being generated by a photovoltaic (PV) system, which results in a constant autonomy level and a consistent self-consumption rate of only 27.76%. As a result, the system is entirely dependent on external energy sources, which not only leads to higher operating costs but also increases vulnerability to price fluctuations and supply shortages. Possible reasons for the lack of PV production could include the absence of an installed system, technical issues, or seasonal factors such as low sunlight.

The energy consumption of the system fluctuates between 0.250 kWh and 1.07 kWh, with a median of 0.658 kWh. This indicates a stable base load, supplemented by occasional peak loads caused by intensive use of specific devices. The consistent base load suggests the operation of continuous consumers such as heating or cooling systems. Despite the predictability of this consumption pattern, the lack of self-production amplifies dependence on external energy sources.

Optimization of the system could be achieved by installing a PV system. A properly sized PV system would allow at least part of the energy demand to be covered by renewable energy, thereby reducing reliance on external sources. Additionally, a battery storage system could store excess energy for use during periods of low production, such as at night or on cloudy days. This would significantly increase both the autonomy level and the self-consumption rate while also improving supply security.

3.2 New Buidlings (Greenfield)

Table 2 “Greenfield”-Parameter System 1(160 qm^2) and System 2 (130 qm^2)

size single family house	160 qm^2	130 qm^2
electricity consumption	4800 kWh	3000 kWh
gas consumption	0 kWh	0 kWh
PV panel	8 kWp	10 kWp
Battery	10 kWp	15 kWp

3.2.1 Single Family House with Renewable Energy (PV, Battery Storage)

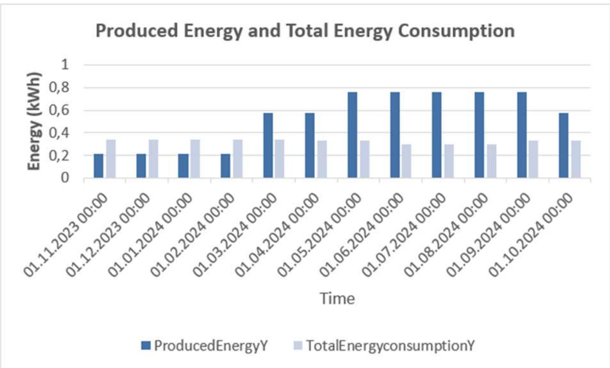

Figure 5
“Greenfield” Total Energy Consumption System 1 (160 qm^2)

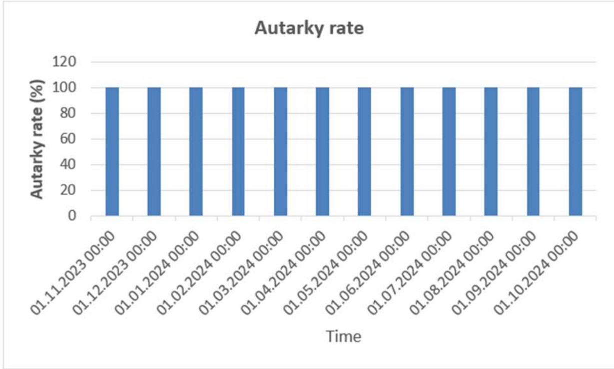

Figure 6
“Greenfield” Autarky Rate System 1 (160 qm^2)

The system shows an average autonomy rate of 64.67%, indicating a significant dependence on external energy sources. While the autonomy rate occasionally reach-es 100%, there are also periods with 0%, during which the entire energy demand must be covered externally. This highlights the inconsistency and inefficiency of self-production.

Energy consumption fluctuates between 0.161 kWh and 0.345 kWh/15 minutes, with an average of 0.234 kWh/15 minutes. The energy generation averages 0.150 kWh/15 minutes, with peaks reaching 0.763 kWh/15 minutes. Without sufficient battery storage, the self-produced energy remains unused, especially during periods of low PV generation, such as at night or in poor weather conditions.

The analysis shows that low PV production and higher energy consumption lower the autonomy rate. Improvements such as expanding the PV system and increasing storage capacity could enhance autonomy, cover energy demand more efficiently, and reduce dependence on external sources.

The analysis of the system makes it clear that the combination of lower PV production and higher energy consumption leads to a significantly lower autonomy rate. Without adequate battery storage, the generated energy cannot be stored and utilized during periods of low production or high consumption.

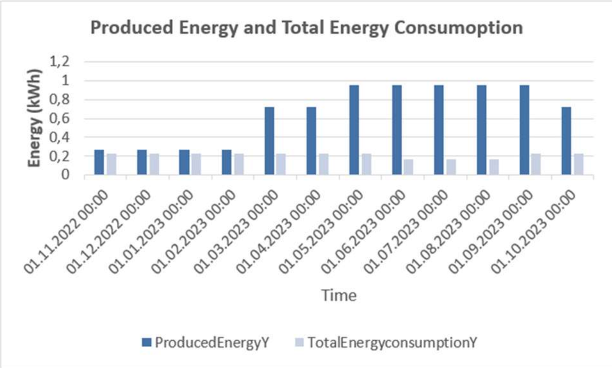

Figure 7
"Greenfield" Total Energy Consumption System 2 (130 qm²)

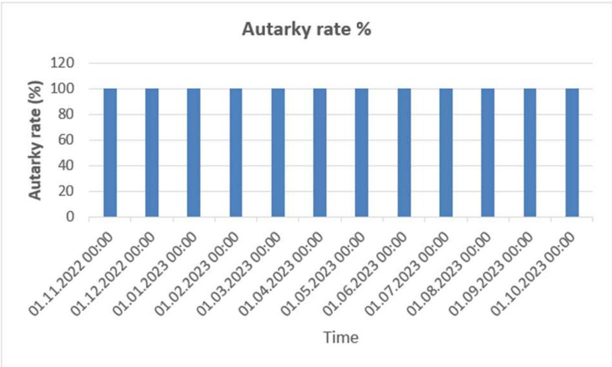

Figure 8
"Greenfield" Autarky Rate System 2 (130 qm²)

The analyzed system shows an impressive average energy independence of 100%, covering its entire energy demand from self-production. Excess energy generated during periods of high sunlight is efficiently stored in batteries, maintaining autonomy even during times of low PV production.

The PV system generates an average of 0.187 kWh/15 minutes, with peaks of up to 0.953 kWh/15 minutes. This high performance under ideal conditions ensures that the energy demand is fully met, while excess energy can be stored. During periods without PV production, such as at night, the battery storage reliably takes over the energy supply, ensuring continuous self-sufficiency without external dependencies.

The system's energy consumption is stable and relatively low, with an average of 0.147 kWh/15 minutes. Peaks of 0.230 kWh/15 minutes and a minimum of 0.083 kWh/15 minutes show that the demand is predictable, making it easier to dimension storage systems. The high efficiency of energy storage and usage minimizes losses and maximizes the system's sustainability. This not only increases supply security but also makes an active contribution to reducing CO_2 emissions.

Table 3 Comparsion of Energy Values "Greenfield" System 1 and System 2

Parameter	System 1	System 2
Average self-sufficiency rate	64.67%	100.00%
Maximum self-sufficiency rate	100%	100%
Minimum self-sufficiency rate	0%	100%
Average energy consumption	0.234 kWh/15 min	0.147 kWh/15 min
Maximum energy consumption	0.345 kWh/15 min	0.230 kWh/15 min
Minimum energy consumption	0.161 kWh/15 min	0.083 kWh/15 min
Average energy generation	0.150 kWh/15 min	0.187 kWh/15 min
Maximum energy generation	0.763 kWh/15 min	0.953 kWh/15 min
Dependency on external sources	High during periods without PV output	No dependency due to sufficient storage and PV capacity

4 Results: Comparsion of Energy Autonomy in Different Systems – Single Family House

In summary, the first system faces significant challenges due to low PV production and insufficient storage capacity. The higher energy consumption further increases dependence on external sources, particularly during periods without self-production. Expanding the PV system and increasing battery storage capacity could significantly improve energy autonomy and make the supply more sustainable.

In contrast, the optimized system offers great potential for an independent and sustainable energy supply. The combination of a high-performance PV system and well-sized battery storage enables reliable self-sufficiency and significantly reduces the need for external energy sources.

Both systems highlight the central role of an efficient PV and storage strategy. While the first system still has considerable room for improvement, the optimized system serves as a compelling example of the effective use of renewable energy and its contribution to a more environmentally friendly energy infrastructure.

The two systems show clear differences in energy autonomy and efficiency. System 1 achieves an average autonomy of 64.67%, meaning it often relies on external energy sources. Particularly critical are periods with 0% autonomy, where the entire energy demand must be met externally. In contrast, System 2 maintains a constant autonomy of 100%, as it meets its entire energy demand through a powerful PV system and well-sized battery storage – even during periods of low PV production.

The energy consumption of System 1 (0.234 kWh/15 min) is higher than that of System 2 (0.147

kWh/15 min), showing greater fluctuations and higher peak loads (0.345 kWh/15 min vs. 0.230 kWh/15 min). This instability complicates the efficient sizing of energy storage. Additionally, System 1 produces on average less energy (0.150 kWh/15 min) than System 2 (0.187 kWh/15 min), and peaks at only 0.763 kWh/15 min, compared to 0.953 kWh/15 min for System 2, indicating a lower PV capacity.

In conclusion, System 2 demonstrates the potential of an optimized combination of PV system and battery storage: full energy independence and efficient use of renewable energy. System 1, on the other hand, remains dependent on external sources due to weaker PV production and limited storage capacity. To improve System 1, the PV system and battery storage should be expanded, and load management strategies should be implemented to increase autonomy and efficiency. System 2 already represents a compelling example of a sustainable and independent energy infrastructure.

5 Conclusion

Community microgrids offer an innovative solution to the challenges of energy sup-ply in a decentralized infrastructure. They enhance energy efficiency by minimizing transmission losses and optimizing self-consumption. At the same time, they increase resilience and grid stability through autonomous operating modes and decentralized structures. Despite the challenges in implementation, the potential of community microgrids is enormous. With the right technological, political, and societal support, they can play a key role in the global energy transition. The further development and expansion of community microgrids require continuous innovation in storage technologies, control systems, and communication technologies. At the same time, sup-port through political measures and funding programs is essential to remove regulatory barriers and promote investments. Close collaboration between governments, companies, and local communities will be crucial to realize the benefits of community microgrids worldwide and create a sustainable, resilient, and equitable energy future.

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