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Concepts and Examples of Carbon-Free, Self-Sufficient Local Energy Systems

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The necessity of the “green revolution” in the field of energetics is not a question anymore; however, switching the current fossil fuel-based energy ecosystem to a fully renewable-based one poses enormous challenges. The historical structure of the present, centralised energy production infrastructure, as well as the fundamentally different characteristics of the three main fields of usage (electricity generation, heating and transportation), are among the most substantial hindering factors. The future energy system has to be much more flexible in several respects, with a fundamental contribution of smaller, independent energy communities. The current study focuses on the realisation aspects of such a small-scale energy community (or micro/nano-grid), considering the suitable technological solutions as well as the cost concerns. A high number of pilot projects and case studies around the world prove that the technical feasibility of a local grid/energy community is no longer a question. The real challenge is to find the appropriate incentives and strategy to catalyse the required transition at the legislation, system operator and end-user level as well. The outcomes of the present work contribute to this goal by pointing out the application potentials of a modular, scalable microgrid system based on a currently running microgrid-realization project at the ZalaZONE proving ground.

1. Introduction

The global energy system has been undergoing massive changes in the last century, and these changes are continuing to happen nowadays. These processes are motivated by technological improvements as well as by political, social, and economic factors. The first big step towards a deliberate energy system was made together with the First Industrial Revolution: the mechanisation of different production activities required a central power source (typically a steam machine), from which the energy was distributed through mechanical connections (shafts, belts, and gears). This made physical human work significantly easier, resulting in higher productivity and efficiency, along with further social benefits. The usage of “machine power” was, however, limited to a physically close environment. Even though mobile steam machines were invented and used in the first half of the 19th century, the real mobilisation of energy – making it available for large populations over large distances – was started at the end of the1880’s. Interestingly, the two most widespread energy sources were put into practice at the same time. On the one hand, the spreading of the public electricity network started after the demonstration of the light bulb at the International Exposition in Paris (1881). Until the end of the decade, electricity systems – firstly supplying public lighting – were installed in many cities around the world. On the other hand, Nicolas August Otto created his first internal combustion engine in 1776, which was built as a practically usable vehicle by Karl Benz in 1885. In this decade, both solutions were developed rapidly in parallel: internal combustion engines served the mobile energy needs, while the electric grid became a dominant energy source for households.
After more than a century of rivalry, internal combustion engines and other fossil fuel-based power sources were started to recede into the background slowly but surely, due to their negative environmental impact. The electrical form of energy, on the other hand, has gathered more and more ground, especially when produced from renewable sources. It should be mentioned that other solutions are still on the table to eliminate or compensate for the effect of global warming due to the drastically increased CO_2 emissions: One can mention

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renewable (hydrocarbon-based) fuels, e.g., bio-ethanol (Vásquez Llanos et al., 2024), green hydrogen (Barros et al., 2024) as well as nuclear energy source – latter being not renewable, but inherently CO_2-free and available for thousands of years. Further ideas target the reduction/reversal of the effect of increasing CO_2 content in the atmosphere – even by capturing and storing it (Keith et al., 2006) or by converting CO_2 to renewable fuel (Falcinelli, 2020). Geoengineering, indeed, targets interventions with compensating effects, e.g., dispersing sun radiation reflecting materials in the atmosphere (Maruyama et al., 2015). Despite the wide variety of potential solutions, the spreading of renewable electricity production and the electrification of the energy (and transportation) industry seems to be unstoppable. This process necessitates a paradigm shift compared to the last 120 years in the concept, design, and control of public electricity networks.
The present work collects and interprets recent and expected future trends in the green transition of the energy industry, supporting the conceptual and detailed design of a unique, modular energy source system that is being built at the ZalaZONE proving ground.

2. Technical challenges of green transition

From a bird's eye view, there are clear steps of the green transition in the energy sector: producing electricity from renewable energy sources, replacing fossil fuel-based vehicles with electric ones, and replacing the gas-, oil-, or coal-fuelled stationary energy consumers (heating, industrial applications etc.) to electric solutions. The reality, indeed, poses several hindering aspects from economic, technological and social fields, summarised aptly by the energetic trilemma concept (Grigoryev and Medzhidova, 2020): Energy security, energy equity and environmental sustainability must be fulfilled at the same time. In the following subsections, some concrete problems and difficulties are collected, focusing mainly (but not exclusively) on the technological aspects.

2.1 Centralized vs. decentralised energy system

The principle that big, centralised energy sources make energy generation and distribution easy and efficient was dominant until the very last decade when smaller industrial as well as private entities started to contribute significantly to electric energy generation. Among the different forms of small-scale energy generators, photovoltaic panels (PVs) are outstanding for more reasons that overcome their drawbacks (like moderate efficiency and space requirements):

- Drastic decline in price,
- Simple installation and practically no need for maintenance,
- Long expected lifetime,
- Efficiency is almost independent of size.

The last point is essential, because it eliminates one of the biggest advantage of centralised power generation: the higher efficiency of large-scale realisation. Considering these aspects, it can be stated that using a decentralised or distributed energy generation (DG) is now more and more feasible for consumers from a technological and economic point of view. Considering the energetic trilemma, energy security is the most challenging field due to the limited storage capacity and flexibility of a small local system. For that reason, the vast majority of DG solutions are still connected to the commercial electrical grid, ensuring buffer and backup for extreme situations (Liu et al., 2017) – see Figure 1.

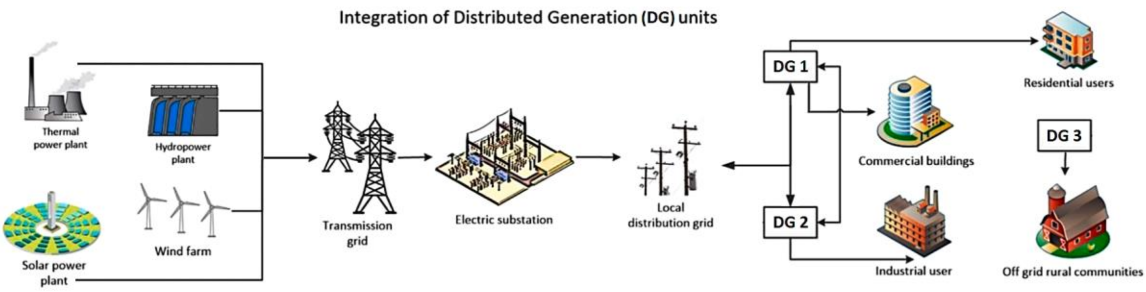

Figure 1: Integration of distributed generators (DGs) into the commercial grid, based on (Gawusu et al.,2022)

The widespread situation – connecting DG systems to the public network just to have a safe energy backup – is not sustainable in the long term because it needs practically a full-capacity centralised system. The renewable capacities, in that case, are installed on top of the public network – this is the case, e.g., in the German energy system (see Figure 2/b). To reach a really effective, cost-efficient energy system based on decentralised, renewable-based generators, there are technically three possible solutions - or combinations of them:

1. Having disconnected, self-sufficient local grids (technically, it is a solution, but not optimal from neither efficiency nor cost point of view)

2. Drastically increasing the storage capacity in the centralised grid – and in parallel, the backup production capacities can be decreased
3. Remodelling the current centralised grid and energy management system to optimise its architecture for a DG-dominated network. It will also need storage- and backup production capacities, but their size, distribution, and utilisation can be optimised.

The scope of the current paper does not allow a more profound evaluation of this problem, but active research is made, and further dissemination will be done in this field by ZalaZONE InnoTech as well.

2.2 Challenges of renewable energy sources

A huge number of different renewable energy generators are technically available, but PV, wind, and hydropower are the most widely used ones (IEA, 2023). The latter can be considered as the most stable and calculable – still having some seasonal fluctuation, but its applicability is limited and strongly dependent on the geographical possibilities. Wind turbines and especially PV panels can be used with much fewer restrictions. Considering investment and maintenance expenses as well leads to a clear understanding of the drastic increase of PV applications in the last years (IEA, 2023). From these trends, it is clear that solar energy will be the highest priority among renewable sources in the next decade(s).

The most challenging aspect of PV (and other renewable) energy sources is the temporal and local fluctuation of energy generation. Availability on the daily and yearly scale follows a trend with minor or major fluctuation, which results in a strongly varying and unpredictable difference between supply and demand. The resulting disadvantageous position in the market is compensated by the governments by various premia systems (Frondel et al., 2022). A further technical consequence is the moderate capacity utilisation of PV and wind-based sources (see Figure 2/a), meaning that the built-in capacity should be several times higher than the real, average energy need.

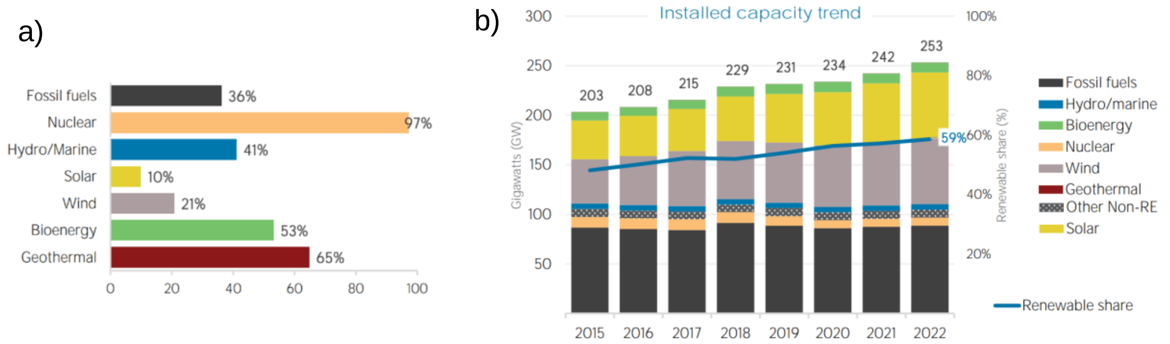

Figure 2: Energy production capacity utilisation in 2021 (a) and installed capacity (b) in Germany (IRENA, 2023)

2.3 Energy storage

To handle the above-mentioned fluctuations and the mismatch of production-consumption characteristics, the controllable producers and system flexibility give us limited room to move. The only comprehensive and long-term solution is the integration of storage capacities, which are comparable in size to the production capacity. Small-medium-size local storage solutions, as well as large facilities, have their role in an ideal system. Table 1 collects the main technologically available electric energy storage solutions with medium-to-high power rates for different timescales and storage capacities.

Table 1: Energy storage solutions and their typical characteristics (based on. Hossain et al., 2020)

Time range	Solution	Storage time	Stored energy	Power output	Application examples
Short	Flywheels	s … min	kWh	kW … MW	Short-term buffer storage
	Supercapacitors	s … h	Wh	W … kW	UPS, Small-medium vehicles
	Superconducting Magnetic Energy Storage	min … h	kWh	MW	Grid levelling, Electromagnetic gun
	(Li-based) batteries	h … day	Wh … MWh	W … MW	Portable devices, EVs
	Compressed Air	h … mo	kWh … MWh	kW … MW	Grid balancing
	Hydrogen Fuel Cell	h … mo	Wh … MWh	W … MW	Vehicles, Grid balancing
Long	Pumped Hydro	h … mo	GWh	MW … GW	Grid balancing

3. Local grid solutions

As mentioned above, local grids can be connected to or fully detached from the public grid. The formation of a local grid can be motivated by technological or economic reasons. Technological reasons can be the absence or inadequate quality of the public grid: in case of military actions, environmental disasters, or simply missing infrastructure, the installation of a local grid is necessary. Another reason can be when the quality of the existing grid is not satisfactory: e.g. for an EV charger, the rated power is not enough, or temporary dropouts are not acceptable in a factory. Economical reasons – like using 100 % of our renewable sources instead of feeding back to the public grid at low price – may initiate the formation of energy communities as well.

3.1 Microgrids

Microgrids are classically small-power, small-capacity solutions physically detached from the public network, for example, an energy container with a power generator that is placed next to a movie shooting site in a desert area. On the other hand, a newly built house with a well-designed renewable energy capacity, storage, and smart energy management system is another type of microgrid, even if attached to the network for energy-safety reasons. A high number of microgrid applications – related to hydrogen form of energy storage – can be found on the website of Enapter, a leading European electrolyser manufacturer (Enapter, 2024).

3.2 Energy communities

The Energy Community (EC) concept was introduced by the European Union and adopted by the Hungarian regulations in recent years (Renewable Energy Directive, 2023). EU Member States had to implement the provisions of the Renewable Energy Directive 2018/2001/EU (RED II) by 30 June 2021 (Krug et al., 2022). Its goal is to take advantage of a shared energy system between the members – by sharing energy production and storage capacities, the dependence on the public grid is minimised or eliminated. To support sustainability goals, the Renewable Energy Community (REC) is defined as producing electricity from renewable sources only.
ECs can be intermediate entities between the public grid and the individual end-users in a future energy system. From the public energy supplier side, it is advantageous not to contract with individual users one by one but with a smaller community, which has more scheduled energy characteristics and less extreme energy needs than the sum of individual consumers. From the user side, the advantages are the distributed investment costs and the lower operational expenses due to a more favourable contract with the public energy supplier. A more sophisticated energy community concept is shown in Figure 3.

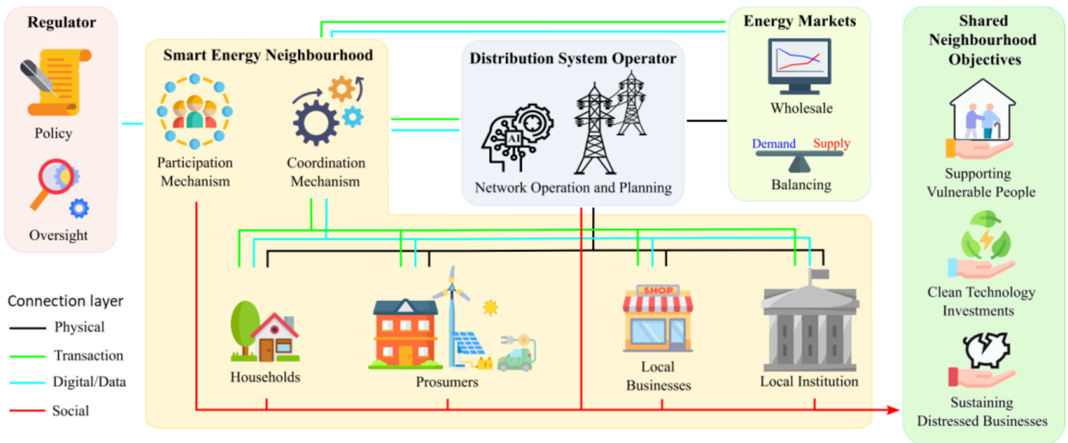

Figure 3: Energy community concept (Savelli and Morstyn, 2021)

RECs are expected to significantly contribute to the green transition in residential energy production and consumption (Trevisan et al., 2023). As detailed above, stakeholders, motivations, and goals of an (R)EC vary widely. The initiation can come from different entities as well – from a private company or local municipality in most cases, but associations, research centres or citizens may initiate RECs too (see Figure 4/a). Regarding the number of energy cooperatives (RECs or other formats before the EU directive), different countries show different trends due to their technological and regulatory peculiarities, but a generally increasing trend has been realised in the last decade (see Figure 4/b). The detailed analysis of energy communities is beyond the scope of the present paper, but several descriptions and analyses can be found on this topic – e.g. (Li et al., 2024).

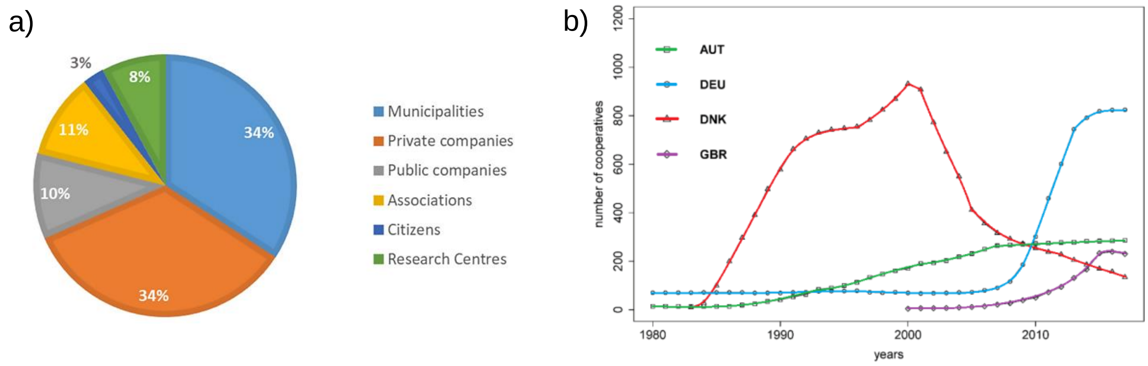

Figure 4: Initiators of RECs in Italy (a) (Krug et al., 2022) and the number of energy cooperatives in different countries (b) (Trevisan et al., 2023)

4. Suggested solution: a modular, scalable microgrid system

The detailed challenges of green transition in the energy industry outlines a clear need for renewable-based energy generator systems in different scales, adapted to the actual energy source- and consumption characteristics. The design of such a system is technically feasible, many application examples can be found around the world. These solutions are, however, uniquely designed and built, resulting a generally long realization time and high building cost. Considering “plug-and-play” solutions, systems consisting of PV panels and a battery unit (together with an energy management system) are available on the market. The flexibility is limited to the variable generation- and storage capacities.

To enhance the spreading of local grid solutions, the proposition of the authors is a modular, scalable energy generator and -storage system with a much wider application range than the above systems. High level of modularity and scalability should be achieved for the energy generation, -storage and -delivery as well. With such a system, the design and installation of local grids can be made much more cost- and time-efficient beside a really wide spectrum of applicability.

At ZalaZONE InnoTech the development of such a system is in progress. Based on the targeted goals, the renewable-based energy module should fulfil the following requirements:

- On-grid and off-grid operation – adapted to the target application, with automated switching between the modes, if necessary.
- Appropriate storage solution and capacity: short- and long-term storage options for energetic- or even cost optimization.
- Functionality in different use-cases: should serve continuous or intermittent, low- or high-power needs. Beside the prior targets, additional functionalities – like cost optimization or even profit realization by peak shaving - are beneficial to be involved as well (Jankowiak et al., 2020).
- Modularity and scalability: meaning the ability to adapt to different energy generation and -consumption scenarios, hosting different (renewable) sources, serving different needs, using different storage solutions.
- A robust but flexible energy management system is essential for the optimal service, performing low-level operational tasks and high-level strategic decisions. They are made based on historical-, actual- and predicted data, considering economic and environmental aspects, using learning algorithms (Xiao and You, 2023).

By realizing these design principles, a highly flexible energetic solution can be offered for a wide range of applications: households, energy communities or even for serving temporary off-grid energy demands.

5. Conclusions

Green transition in the energy sector does not mean only the replacement of fossil-based power plants with renewable-based ones but necessitates the full reconsideration of the energy system. Centralised energy production and distribution will be changed to a decentralised architecture, with all of its technological consequences. Storage solutions will gain considerable importance, and consumers will be interested in taking an active part in the system control instead of being a passive, unpredictable energy sink.

In the present study, based on these considerations, the most important technical aspects of an “ideal” energy source were collected, and the concept of a modular, flexible energy module was stated. It can accelerate the green transition in the energy industry by reducing design and implementation costs. Not only was the idea formulated, but the system was also realised at ZalaZONE InnoTech. The progress of the work, together with more technical details of the solution, will be disseminated in future publications.

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