Cellular Energy Systems – An Approach to Planning and Operating Future's Hybrid Energy Systems

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Abstract—**The future's energy systems will be hybrid systems comprised of fluctuating renewable energy sources, new loads, different storage technologies and sector coupling technologies providing flexibility dispersed geographically and over all grid levels. The rising number of active participants in energy systems makes planning and operating them more complex and increases the demand for adequate control schemes to ensure a reliable energy supply. This paper introduces the Cellular Approach (CA) or Web-of-Cells-Approach (WoC), a system concept specifically tailored to address the numerous challenges arising from the transformations of the world's energy systems. The main principle is to break down the complexity of the whole system to manageable entities, delimited by grid levels and grid extension and ordered hierarchically, hence the name Cellular Approach. The cells locally optimize their technology portfolio, aggregate the results, and interact with neighboring cells. However, the aim of the Cellular Approach is not autonomy, but rather the ability to choose the most efficient way of energy supply out of a number of different options.**

Keywords-cellular energy systems, hybrid power systems, system operation, flexibility utilization

I. INTRODUCTION

The anthropogenic climate change will have severe impacts on the foundations of life all over the planet. The importance of limiting the rise of the global average surface temperature has been laid out in several international studies, most prominent in the reports on global warming by the *Intergovernmental Panel on Climate Change (IPCC)*. In accordance with previous reports, almost all nations have agreed to take action to limit the rise of the global average surface temperature to 2 °C compared to the pre-industrial level in the 2015 Paris Agreement [1]. However, the latest IPCC report from 2018 illustrates that a 1.5 °C-target is necessary to reduce the risk of reaching critical tipping points that would amplify climate change irreversibly [2]. To reach either target, greenhouse gas emissions must be reduced to almost net zero by 2050, especially in industrial nations such as the EU members [3]. This requires an extensive transformation of energy systems across all sectors from electricity to mobility during the next decades.

Many studies on national, European, and international levels have investigated the question for how energy demand can be fulfilled in the future under the guiding principle of achieving and conserving almost net-zero greenhouse gas emissions. Although results differ between countries and regions, the basic take-aways are consistent throughout all studies. Electrical generation will almost exclusively be based on renewable energy sources (RES), namely wind and solar power. Compared to today's nuclear, coal, and gas power plants, the infeed of RES is as volatile as the weather it is derived from. Electrical demand, however, does not correlate with weather but rather the users' behavior, and can therefore, although higher due to e-mobility and electric heating, not be equal to the generation at most times. This implies that an overproduction of electricity must be stored, and an underproduction of electricity must be equalized from these storages. Additionally, the demand for hydrogen, synthetic gas and fuels as well as district heating must be served by the electricity sector through sector coupling since there are no significant renewable sources for these secondary energy carriers. Sector coupling also makes long-term energy storage accessible to the electrical system through power-to-gas (PtG) technologies and conventional thermal generation for periods of low renewable generation. [4]

This paper is structures as follows. After a brief introduction to the key assumptions in this section, section II will derive the motivation for cellular energy systems (CS). Consecutively, section III will elaborate the main principles of cellular energy systems. Finally, before the conclusion in section VI, section IV will touch on a real-world example.

II. MOTIVATION

As a consequence from these changes, the number of active participants in the energy system will rise dramatically over the next decades. Independent from the changes in technology that affect ancillary services and increase complexity further, the optimization problem of the unit dispatch becomes impossible to solve because of time constraints and the enormous amounts of data that need to be acquired and processed. At the same time, this optimization problem is crucial to solve as it directly describes the physical balancing of supply and demand and failure to solve it could result in interruptions and even blackouts.

The increased number of degrees of freedom also affect grid planning as the expected utilization of flexibilities can obviously reduce the necessity of grid reinforcement and extension significantly. However, in order to be able to consider flexibility impacts during grid planning, not only the amount of flexibility available in the grid must be known but also the framework governing the commitment.

Of course, the challenges arising from the energy transition are already visible today, e.g., when weather conditions and therefore renewable generation differ from the prognosis and grid congestions must be solved by redispatching units, countertrading, and other measures. Just in Germany, the yearly expenses for congestions management exceed 1 billion € by far [5]. The underlying reason the insufficient capability of the grid to transport the power from where it is generated to where it is needed, either because the necessary grid extensions are delayed or uneconomic, e.g., for islands and remote areas. The problem is amplified by the design of the electricity market: Although grid models are used during market clearing, the concept is designed for predictable generation and load. Aberrations such as weather-dependent technologies cause the need for downstream interference with market results. Because the past development of congestion management costs has correlated with the share of RES in the energy system [5], it is reasonable to expect them to rise continuously in the future.

The current system design also provides only few incentives for small private investments in flexibilities other than to increase autonomy, e.g., with a photovoltaic (PV) plant and a battery storage. It also generally lacks the ability to make proper use of flexibilities in distribution grids during operation, not only because the system is not designed for it, but also because the decision-making entities do not have access to the necessary information. On the other end of the hierarchical spectrum, large sector coupling technologies providing additional flexibility require close coordination with the gas and heat sectors as their constraints must be considered next to the electricity sector’s constraints. However, inciting such investments and utilizing them in a beneficial way for the energy system can be considered one of the key requirements for a successful transition towards RES-dominated energy systems. [6, 7]

With flexibility representing a way of bridging the temporal gap between generation and load, long-distance and transnational power transmission provide a way the equalize the spatial differences in generation and load. As the direct use of electricity is arguably the most efficient use, grid extension must be considered as an option to increasing flexibility. This implies the existence of a techno-economically optimal combination of flexibility and grid extension and thus this trade-off must be considered during grid planning and operation. The ability of sector coupling to combine the ability to easily store energy, e.g., in the form of synthetic hydrogen or methane, and the possibility to transport large quantities of energy over very long distances through hydrogen or methane pipelines that can carry significantly more power than even HVDC transmission lines add to the complexity of the analysis of this trade-off. [6]

III. THE CONCEPT OF CELLULAR ENERGY SYSTEMS

The main goal of the cellular approach or web-of-cells approach is the technologically, economically, and organizationally efficient utilization of flexibilities and sector coupling technologies by reducing the complexity of system operation. As the name cellular energy system suggests, the main principle of the cellular approach is the division of the energy system into cells. The delimitation of the cells follows in one form or another either the extent of the electrical infrastructure, e.g., the extent of a medium voltage grid, or the ownership structure, e.g., a household. While the delimitation by ownership is also applicable to the cells of customers, the structure of gas and heat grids is usually not congruent with the electrical infrastructure. Gas grids often extend much further and therefore they may belong to several cells. Heat grids are generally limited to a regional level and may also belong to several cells; however, their structure usually requires an individual consideration. The implications of this are elaborated for example in [8]. The division into cells does not implicate autonomy or a microgrid character but is primarily a control aspect. The cells are ordered hierarchically with the number of cells being the largest on the lowest and the smallest on the supreme level with each superior cell incorporating several inferior cells. Each cell can optimize their internal behavior considering the technology portfolio, load and generation forecasts, and the possible interactions with inferior and superior cells., e.g., energy import from a superior cell that has additional generation at low cost. However, the superior cells may require changes in the desired operating point of the inferior cells when necessary, e.g., when the demand for electricity can be increased temporarily by demand side integration or other flexibilities to avoid RES curtailment. By aggregating each cell’s optimization results, the data exchange necessary to facilitate the optimization on each level is reduced to as little as a single power-cost-function.

The optimization of the whole system is an iterative process where local optimization and global optimization work towards each other. By aggregating technologies into cells, the number of participants in the global optimization itself is reduced greatly; and by limiting the local optimization to one cell, the local problem becomes solvable for the organizational unit as well. This way of optimization resembles a common practice from control theory: All local control tasks are performed locally within the governing framework, and only when necessary, the governing control loop takes precedence. With this approach, a discrepancy to the theoretical global optimum remains, however, it is a reasonable assumption that such an optimization is impossible and therefore the discrepancy can be accepted in reasonable boundaries.

The concept of cellular energy systems does not only include the technological side of the optimization problem, but also the economic side. Addressing today’s problems mentioned above, market and system operation grow together to a certain degree depending on the specific project. In Zellnetz2050, for example, system and market operation become one inseparable task [9]. This way, technological restrictions can be prevented by economic incentives efficiently instead of determining the cost of interventions ex-post. Hypothetically, the new approach leads to lower overall system costs. Another benefit is that units, especially on the lower levels of the hierarchical system, can usually operate directly on economic premises ensuring the financial feasibility of such investments for the investing party. Only in extreme situations non-economically driven instructions must be given to a cell. In this process, the trade-off between utilization of local flexibilities and long-distance transmission is automatically solved because the energy prices depend on the availability of energy in the system and possibly the ability of the system to transport the energy to where it is needed. Therefore, the most economic operation point is found in the optimization process of each cell. Although the precise design of the market again depends on the respective project implementing a CS, in general, many working and useful market features from today's concept are maintained in cellular energy systems. The changes mostly affect the combination of concepts, adaptions for the cellular characteristics of CS and improvement on features that appear inadequate for the future. While the changes may not affect market design on lower hierarchical levels, e.g., municipal utility providers, as the entities there are usually not unbundled, on higher levels the proposed market concepts may differ substantially from today's unbundled European concept.

These principles form a framework for the operation of energy systems, both on the technological side as well as on the economic side. The properties of this framework can be incorporated in a simulation model that can be used to analyze the system operation with a given system configuration in advance, or in system planning. One interesting aspect for grid operators are sensitivity analyses investigating different technology penetrations or characteristics, and different grid extension scenarios. Such a simulation tool can also assist investors in deciding for or against an investment as well as the specifics of their investments in relation to the global scenario and grid capabilities.

Therefore, the same framework that enables efficient, reliable, and safe energy supply also enables the development of a more concrete image of the future's energy systems and provides a starting point for more detailed, hands-on investigations into cellular energy systems.

IV. The Cellular Approach and Today's Hybrid Power Systems

Today's hybrid power systems on islands and in remote areas are a prime field of application for the concept of CS. These systems usually possess a diverse generation portfolio based on renewable generation as well as conventional backup or base-load generation in combination with different storage technologies and, where technologically possible and economically feasible, a connection to another energy system. Often, such systems must also be able to function autonomously in case the outside connection fails or undergoes a scheduled outage, raising an additional constraint for planning and operation.

Now, such an island could be considered a cell, superior to generator cells, storage cells, and customer cells and inferior to a larger cell, e.g., spanning several islands or the mainland system. Using the framework of a cellular energy system, the island cell can now determine the techno-economically most efficient way of meeting the energy demand and managing renewable over- and underproduction. Additionally, the inferior cells would face a defined, consistent scenario to evaluate their own portfolio and investments. At the same time, investment decisions regarding units directly coupled to the island cell become much more complicated as both the consumers below the island cell and above make their own investment and utilization decisions that affect the decisions of the medium-tier cell. The framework of a CS may help to alleviate the difficulties by providing harmonized conditions for all system participants and therefore a way to estimate the developments in other parts of the system for each entity.

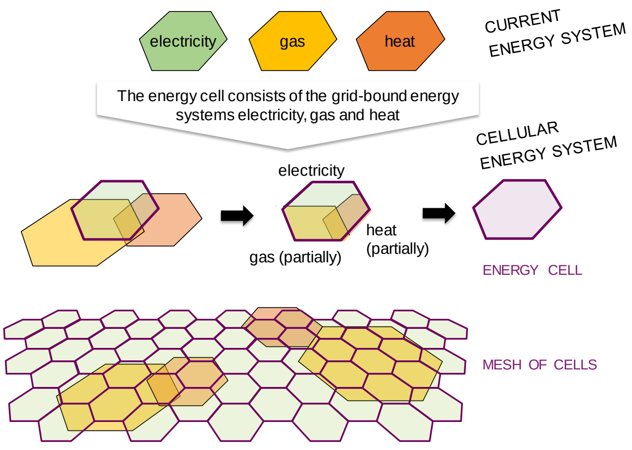

Figure 1. Delimitation of ECs [8]

V. ZellNetz2050 – An Example Project

ZellNetz2050, a German research project funded by the Federal Ministry of Economics and Energy, aims to provide a proof-of-concept for the principle of CS on all hierarchical levels and during both operation as well as planning. Thereby, the CA is applied following a 'brownfield' approach, i.e., considering existing infrastructure and the feasibility of the necessary transformation pathways. Central aspects are a comprehensive structural model including energy cell (EC) definitions and relations, and a novel market concept specifically designed with the structural model in mind.

In ZellNetz2050, the EC delimitation strictly follows the electrical system; however, an EC may contain any number of generation, consumption, storage, and sector coupling technologies from every energy sector. Gas and heat grids then belong to several ECs. (see Figure 1). The focus is set on the electrical grid due to its volatility and limited storage capability. As mentioned above, an EC does not have to have to ability to physically balance itself but instead is supposed to find the optimal balance between local balancing and im- or export. To make this determination, each cell is accompanied by an energy cell management (ECM) unit that monitors, controls, and regulates the relevant supply infrastructure as well as energy and information flows of an EC. Depending on the type of cell, ECM can be further split into a system operator (SO), the decision-making entity, and a system controller, a technological entity implementing the SO's decisions. Because the tasks of the ECM depend on the hierarchical level of an EC, three energy cell levels (ECL) are defined: ECL A contains all end-use cells, ECL B the distribution grids and ECL C the transmission grid(s). [6, 8]

The proposed market concept is based on an integrated market and puts market and grid operation into the responsibility of independent system operators (ISO). The market design follows the hierarchical structure of the ECs and differentiates between local ISOs (LISO) on ECL B and a central ISO (CISO) on ECL C. The market clearing is organized by LISOs and CISOs jointly and a strong interdependency exists between both groups. One of the key aspects of this market design is the introduction of local marginal pricing by the CISO to consider grid constraints already during the market clearing. In concurrence with the basic idea of the CA, the main task of the LISOs is to aggregate the complex bids of the cells on ECL A considering grid constraints for the market clearing of the CISO and the subsequent disaggregation of the market clearing result. Therefore, the CISO only interacts with a manageable number of LISOs, reducing the complexity of the optimization problem on this level. The LISOs receive their complex bids from the underlying units. Therefore, the task of the ECM on ECL A is to create this information by optimizing the end-user cell and to communicate with the LISO before the aggregation and after the disaggregation. Several end-user cells may be managed by a unit manager, for example to provide *unit operation as a service.* [6, 9]

To provide the proof-of-concept for this system, two simulation models are used. An “offline” model is used to show the general feasibility of the proposed system and market concept in a time-series simulation over a full year and across all hierarchical levels with full power-flow models of the German transmission grid and several 110 kV-, 20 kV-, and 0,4 kV grids. This simulation framework will also be used to investigate sensitivities like limited grid capabilities, different degrees of flexibility penetration etc. The offline simulation will be accompanied by an “online” simulation, i.e., a real-time simulation of the electrical grid considering the frequency response in 100 ms steps proprietary of DUtrain GmbH. This simulation features a control room interface enabling the investigation of a human operator’s interaction with the CS. [6]

VI. CONCLUSION

The transition of the world’s energy systems brings up several challenges. Although there are many possible solutions, no clear image of the future of our energy systems or the transformation path to reach them exists. The concept of CE is a contribution that incorporates existing, functioning concepts and techniques but adds promising novel elements where needed to provide a system concept that simplifies planning and operation of the future’s energy systems as much as needed to perform the supply task adequately, economically, securely, and safely. By providing a uniform framework for system operation, the CA/WoC is also applicable for system planning as simulation tools can be developed that allow a prognosis of the flexibility, sector coupling, and transmission utilization for need-owners.

The purpose of this paper was the introduction of the concept of cellular energy systems and its capability to address the challenges of the energy transition in a more general way. Different derivatives of this general concept exist, namely the European ELECTRA Web-of-Cells project and the German ZellNetz2050. CS remain an interesting field of research and application with several real-world projects carrying ‘cellular’ in their name already underway. However, many of these projects aim towards an increased autonomy for their ‘cell’ and therefore do not fit the system designed here as they leave out the systemic point of view.

FURTHER READING & FOLLOWING SESSION PAPERS

Details about two large projects regarding the Cellular Approach or Web-of-Cells-Approach are published under [8, 9, 6] (for the German ZellNetz2050) and [10, 11, 12] (for ELECTRA Web-of-Cells). Of course, other publications exist, but in the opinion of the authors the references given here provide an overview over each project.

The next three papers in this session discuss various aspects of CS. In the paper “Initial Case Studies Conducted on Cellular Energy Systems at the District Level” by Uhlemeyer et al., two real-world application projects in Germany on lower hierarchical levels and their results are presented. Schinke-Nendza et al.’s paper “Regulatory and Policy Aspects for a Cellular Design of Electricity Markets”, several issues regarding the design of electricity markets and the connected regulatory challenges are analyzed. Finally, in Hawker et al.’s paper “The problem of resilience in multi-carrier cellular systems: responsibilities and regulation”, the impact of sector coupling on the resilient operation of energy systems is discussed.

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