Initial Case Studies conducted on Cellular Energy Systems at the District Level

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***Abstract*— Cellular energy systems support local cross-sectoral energy balancing to optimize the integration of renewables into the energy system. In this paper, two initial case studies are presented in which districts are investigated and some basic insights into the future design of decentralized energy system concepts can be derived. It is shown that flexibilities such as battery storages and power-to-gas plants can reduce boundary violations in the electric grid, but that grid expansion cannot be prevented in future scenarios, only delayed.**

Keywords- cellular approach, cellular energy systems, sector coupling, self-sufficiency, district, storage, photovoltaics

I. INTRODUCTION

The hypothesis behind the cellular approach (CA) [1] is that an almost complete defossilization of the energy system in Germany is not possible without the local energy balancing of decentralized renewable energy with flexibilities across energy sectors. Electricity generation in Germany is changing from a centralized system of large power plants to a system with millions of small generation units. This lead to a renewable energy share of 50,5 % in 2020 [2]. When considering the total energy demand, i.e. including heat and transport, it amounts only to 18 % [3]. Therefore, sector coupling in particular will play a decisive role in the next decade in order to increase the overall share of renewable energy. This sector coupling can be implemented e.g. by large-scale power-to-gas (PtG) and power-to-heat plants. However, the subsidiarity principle of the CA leads to the thesis that generation, conversion and use of energy should be done at the lowest feasible level. For example, electricity could be generated by photovoltaics (PV) in the smallest energy cell: the household or building. The energy could be stored in battery storage systems (BESS) and electric vehicles (EV) or electric heat pumps (HP) could be supplied with this energy. This creates local, decentralized self-generation systems that reduce the load on the grid by reducing peak demand and feed-in times. At the upper cellular level, balancing could be continued in districts through the associated low-voltage grids. Here, households can be optimized collectively so that the residual load to the upper level, the medium-voltage grid, is reduced. This hierarchical system supports optimal grid utilization. Currently, there is no systematic legal and regulatory basis in Germany to easily implement such optimized cellular energy systems.

The techno-economic viability of cellular energy systems at the district level under current German conditions has been investigated in various initial case studies [4–12]. In this paper, two of these initial case studies are analyzed representatively in order to show the key parameters of decentralized energy systems and to give conclusions for the further development of multi-energy systems consisting of energy cells.

II. STUDY: CELLULAR DISTRICT - FUTURE ENERGY SUPPLY IN A SUBURBAN DISTRICT

A. *Description of the energy cell and aim of the project*

The project “Cellular District - Future Energy Supply in a Suburban District” [4] [5] [6] contains the investigation of a German suburban area with a low-voltage grid and a low-pressure gas grid. The area consists of 175, one-, two- and multi-family houses within an area of approximately 0.15 km². The aim of the project was to investigate how the future energy design of a suburban district could be shaped by considering a local energy generation and balance. The analysis considers the influence of the increasing energy demand and feed-in on the energy supply, grid utilization and cost-effectiveness.

B. *Investigated scenarios*

In the district, it was investigated how the equipping of the buildings with different technologies such as EV, HP, PV, BESS, micro combined heat and power plants (CHP) and PtG systems could be implemented. Especially the effects on the electrical grid load and the self-sufficiency of the buildings and the district were analyzed. In addition to these technologies, an extensive study of the existing building stock was also conducted. For this purpose, the previous status quo heating technologies were determined and the heat demand was calculated. Based on this data and an assumed renovation rate of two percent, scenarios were created for the next decades, where the 2030 and 2050 scenarios were examined. In particular, a distinction was made between use cases: base case, use case I, use case II and use case III A and B. Table 1 shows the technology combinations of the use cases.

Table 1. Use cases and technologies

Use case / Technology	Base case	Use case I	Use case II	Use case III A	Use case III B
PV	x	x	x	x	x
EV	x	x	x	x	x
BESS		x		x	
CHP & HP			x	x	x
PtG				x	x

The five use cases were investigated for three different future scenarios. As it is shown in Figure 1, the study includes three scenarios of EV, HP and PV expansion. The 2030 and 2050 scenarios were realistic scenarios considering climate neutral constraints coming from the Paris agreement. The *Max PV* scenario represents the maximum expansion case of PV and EV in order to investigate how this would affect the grid.

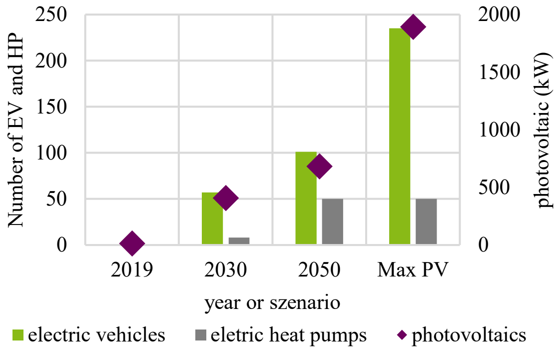

Figure 1: Number of EV, HP and capacity of PV in the district

The largest driver in districts for renewable electricity generation is PV. The entire district has a PV potential of nearly 1.9 MWp. This is a tremendous amount of power compared to the local grid transformer capacity of maximum 1 MW.

C. Grid load, self-supply and economic efficiency

In this section grid load and self-supply results and economics are presented. These results are based on power flow calculations with the scenarios and use cases shown beforehand. Preliminary to the load flow calculation, the battery storage capacities, among other things, were designed to achieve an optimum between self-sufficiency and costs. As shown on Figure 2, the number of boundary violations in the investigated grid will increase in the next decades. In the analyzed district, the boundary violations are only induced by PV. In realistic cases, these are still manageable with 500 h/a. With a maximum PV expansion, significantly higher boundary violations and more extensive grid expansion are expected. In comparison, only a few boundary violations occur in the 2030 scenario.

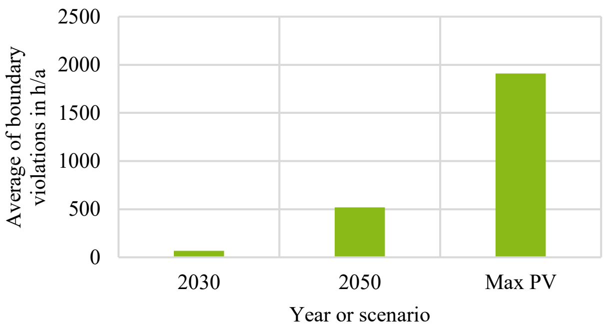

Figure 2: Average of boundary violations per scenario or year

During the analysis of the different use cases (see Figure 3), in which the technologies vary, the boundary violations can be reduced. Figure 3 shows therefore the average results of the scenarios in each use case. The electric self-sufficiency in the base case is in average 35 %. It can hardly increase in the 2050 trend and Max PV scenarios. When considering the technology variation in use case I or II, the degree of electrical self-sufficiency can rise to 61 %. When considering the energetic self-sufficiency including the heat demand, the results are lower. The analysis of the present value of the different technology combinations shows that the Max PV use case causes significantly higher costs than the trend use case. Negative present values are also achieved, so that there is no economic viability in the Max PV scenario, but in the trend scenario there is.

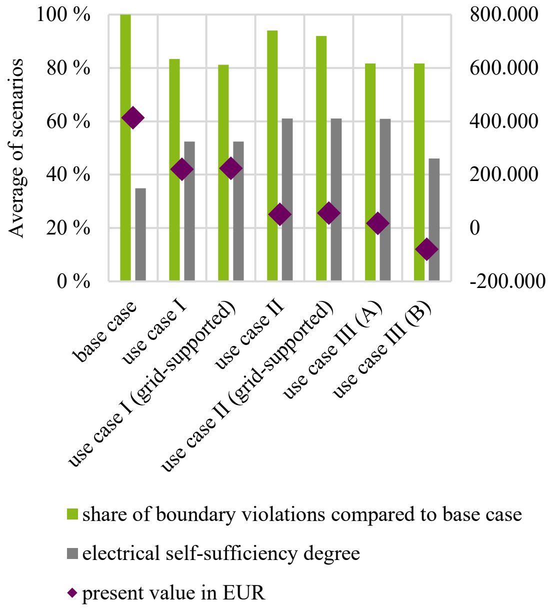

Figure 3: Comparison between the share of boundary violations, the electrical self-sufficiency degree and the present value

D. Key results of the project

The evaluation of the load flow calculation shows that self-supply systems like prosumers have an influence on voltage problems and thermal equipment overloads in the grid. Especially the PV induced boundary violations should be possible to reduce. In the investigated district, the boundary violations were reduced by an average of between 5 and 20 % compared to the base case (see also Figure 3). The degree of electric self-sufficiency increased to values of 35 % on average in the base case and up to 61 % in use case II. The calculation of the economic net present value, including the costs of refurbishment, technology investments, grid expansion and operating costs, showed that the self-supply systems without subsidies or under the current framework conditions are less economical in the use cases than in the base case. The project showed how a cellular district of the future could look like by using the presented technologies. Thereby it demonstrated that an integration of household sector coupling (EV and HP) together with electricity generation by PV can be a logical solution for future district energy supply in districts and only a substantial PV integration can lead to electricity grid boundary violations and thus to grid expansion.

III. Study: Electric City Neuss – Multi-Energy Carrier Districts of the Future

A. Description of the energy cell and aim of the project

In the ongoing project "Electric City Neuss (ElCiN) - Multi-Energy Carrier Districts of the future", several parts of a city are being investigated and field-tested to see how flexibility can be integrated into the energy system using smart grid controllers [7]. The focus here lies particularly on the combination of decentralized generation on the outskirts of the city (wind, PV) and the flexibilization of loads in households and commerce. A smart grid controller (ElCiN-System) with energy and grid forecasts characteristics is intended to react to boundary violations in the grid caused by peaks in generation and demand. The limit violations are then predictively solved by adjusting generation or demand. The grid serviceability is examined as the primary control objective for the ElCiN-System (currently the only control objective, taking costs into account; others may be implemented in the future). A grid-serving approach automatically improves the efficiency of the system, since in cases of high load or feed-in, the load and feed-in are aligned. Grid-serving can result in costs to the flexibility provider, so a market-based approach to compensation was used. Based on all these findings, the ElCiN-System was implemented in Matlab as a preventive acting system, which can be seen as a complement to a grid automation system. Since such systems are not yet available in this application form ready for the market, for the practical application of the system in the field test, the flexibilities are not calculated at the cell level in the cell itself, but in the ElCiN-System at the unit level. The main aim in the project is to investigate multi-energy carrier districts of the future and the design of a decentralized control system. The coupling of the sectors electricity, gas, heat and mobility on the district level will be analyzed. In particular, the best possible integration of renewable energies and sector coupling into the power grid will be tested in practice by using the ElCiN-System. For this purpose, flexible multi-energy loads, generation units and storages are to be controlled in an optimized way to prevent boundary violations. In this way, local energy balancing will be implemented as in the cellular approach. The concept is shown in Figure 4. There is shown, that the market participants communicate with the network operator. The flexibility is predicted and an ElCiN-Signal is transmitted.

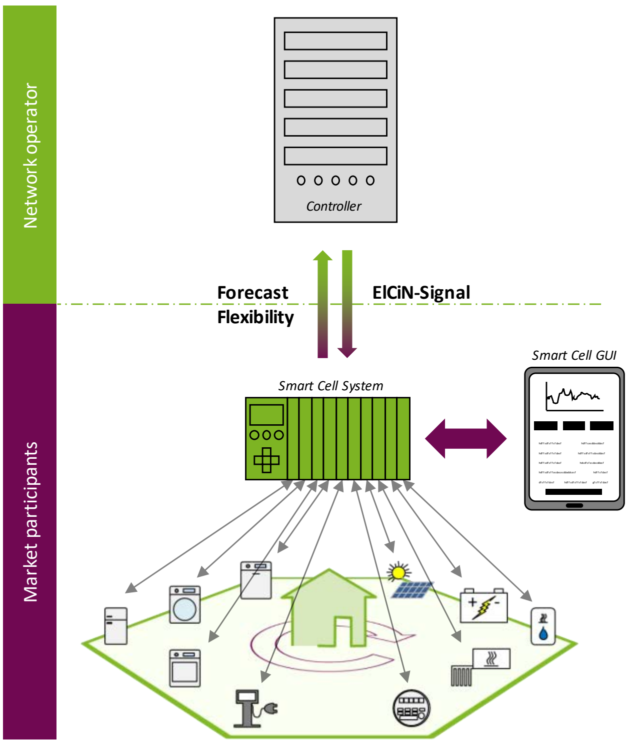

Figure 4. Scheme of the cross-sectoral approach in ElCiN

B. Investigated scenarios and realization project

A comprehensive potential and impact analysis of the changes in the electricity, gas, heat and mobility sectors was carried out for the districts in the project. The optimization is carried out according to the cellular approach in the lowest cell level up to the maximization of its own economic efficiency. For this optimization, a multi-energy optimization controller must exist. The optimized cells can potentially provide flexibilities to the higher-level cell (low-voltage grid) for optimization (e.g., grid-serving). In the low-voltage grid, an intelligent control system is needed for optimization (ElCiN-System).

In the project, the ElCiN-System will be functionally tested on a simulative level in order to prevent grid problems. In addition, a field test in two low-voltage grids will be conducted to prove its suitability for practical use. The cost-technical evaluation of the system will be carried out in comparison to other innovative and conventional grid optimization options. The flexibility determination of different actuators (including sector coupling units) is possible and can be integrated into a preventive control system

C. Grid load, self-supply and economic efficiency

1) Use of BESS in districts to avoid boundary violations

Within the project, it was investigated whether and to what extent BESS can prevent boundary violations [7]. Different configurations with respect to the storage concept, the location configuration, the charging strategy and the capacity of the BESS were considered. The resulting boundary violations are shown in Figure 5. On the x-axis the scenarios of the paper are shown. The comparison case is the reference case (≙ ref). The following applies to all other scenarios: The first character represents the storage concept (d ≙ district, h ≙ household), the second character for the site configuration (c ≙ central, e ≙ end of grid and d ≙ distributed), the third character for the charging strategy (d ≙ direct, p ≙ peak shaving and g ≙ grid-serving) and the last character for the capacity of the BESS (1 or 2 kWh/kW of PV).

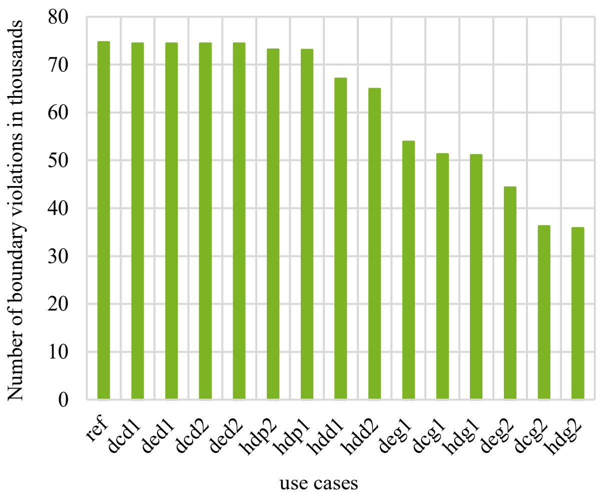

Figure 5: Boundary violations in the investigated scenarios with battery storage units

This shows that mainly the charging strategy and the increase of the BESS capacity has an influence on the lowering of the boundary violations. Overall, however, it shows that it was not possible to prevent all boundary violations with the investigated combinations. This would only have been possible by a high over dimensioning of the resources, related to the primary purpose of PV energy storages. Therefore, this study shows that a sensible configuration and the grid-oriented use of BESS in districts can reduce boundary violations, but cannot avoid them from an economic point of view.

2) Techno-economic examination of the usage of a PtG system in districts

Close to the investigated district there are wind turbines feeding renewable energy into the medium-voltage grid. In the future, boundary violations caused by feeders and loads are to be expected in the medium-voltage grids as well as in the low-voltage grids. In order to store energy in the long term, PtG units will produce hydrogen. The additional load through PtG can absorb surplus renewable electricity and thus avoid a shutdown of the wind turbines, which corresponds to a waste of energy. Figure 6 shows how the dimensioning of the PtG units affects the possible number of full load hours. This was examined for different hydrogen concentrations in the natural gas grid. It can be seen that at a concentration of 2 %, which can currently be implemented without problems, only about 200 full load hours would be possible in the range of a realistic dimensioning of at least 300 kW. With a realistic addition of up to 10 % hydrogen concentration in the near future, significantly higher full load hours of up to 544 h/a are possible.

However, there are two major problems: First, the full load hours are low due to the low surplus hours that an economic operation of a PtG unit is not possible. Second, despite the PtG unit, boundary violations remain (see also Figure 7), which make a grid expansion necessary and a grid-serving application is then no longer necessary, at least for the medium-voltage level.

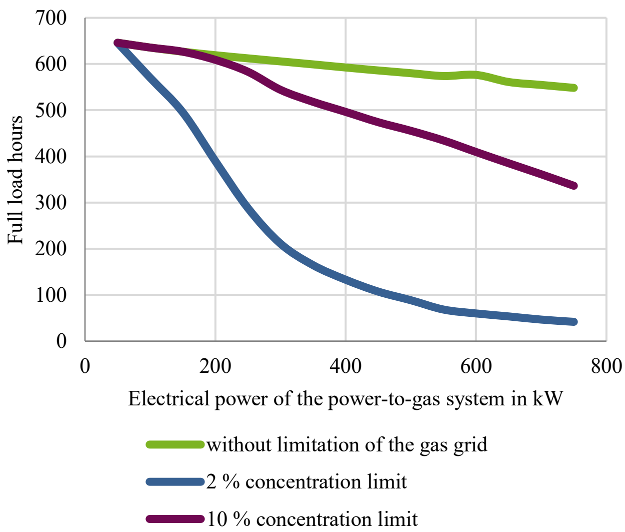

Figure 6: Full load hours of a PtG unit

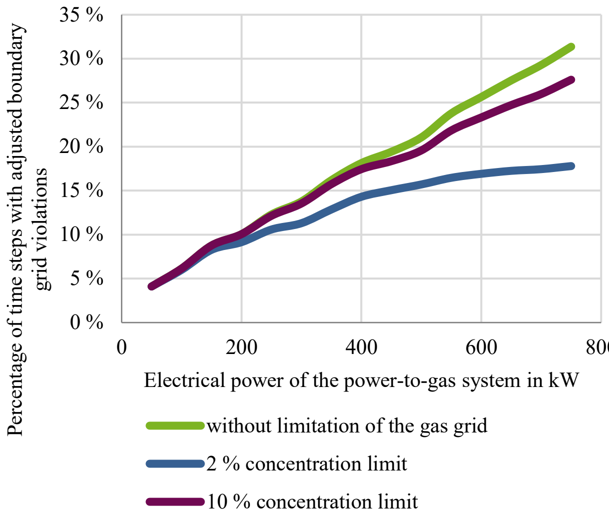

Figure 7: Boundary violations remedied by the PtG unit

D. *Key results of the project*

The future supply structure, which is largely determined by the addition of new distributed loads and generators, will tend to be dominated by a load surplus in the field test areas and thus lead to load-related grid congestion. BESS can reduce the number of limit violations, but not completely avoid them. PtG to avoid feed-in related grid congestion at the medium voltage level is not an economic option in this area compared to conventional grid expansion, as the full load hours due to nearby renewable energy generators are too low compared to the load.

IV. Comparison of the Case Studies

A. *Flexibility use in low and medium voltage grids*

In the Cellular District project, the focus was on investigating different technology combinations. In contrast, the ElCiN project focused more on the dimensioning and positioning of BESS and PtG units. Nevertheless, both projects came to a similar conclusion with regard to the use of flexibility in distribution grids. The comparison of the results of the two initial case studies shows that in both cases, with different districts and system variations, it does not make economic sense to remedy boundary violations in the electrical grid only with BESS or PtG systems. The systems would have to be significantly larger than necessary for the primary purpose. It becomes clear that distribution grid expansion is inevitable from a certain degree in many grids due to increasing electrification. However, flexibilities are a useful way to utilize the grids more efficiently and to delay grid expansion. In this way, staggered grid expansion can be better managed.

B. *Self- sufficiency degrees of districts*

However, the study of the degree of self-sufficiency shows that the grid efficiency can be increased without compromising the comfort of the users if flexibilities are used according to demand. Even if boundary value violations in the low-voltage grid cannot be completely eliminated, the grid-serving use makes sense for all superimposed grid levels, since the overall grid use is thus made more uniform.

V. Conclusion and Outlook

This paper shows that there are many technically feasible options to produce and consume parts of the required energy even at the lowest energy cell level. Not all of these options are economically viable under current conditions and production capacities. BESS can increase efficient grid utilization, but cannot prevent limit violations beyond a certain level of new loads and feeders. PtG plants can convert excess renewable energy to hydrogen and thus prevent curtailment, but the available full-load hours are so low that economic operation is not possible in the cases considered. In addition, grid expansion could not be prevented here either. In the future, more and more districts and urban areas will approach the goal of a sustainable cellular energy supply.

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