# RESIDENTIAL QUARTERS AS INNOVATIVE ENERGY CELLS

Linda GÜNTHER
Wuppertal University – Germany
linda.guenther@uni-wuppertal.de

James GARZON-REAL
Wuppertal University – Germany
james.garzonreal@uni-wuppertal.de

Markus ZDRALLEK
Wuppertal University – Germany
zdrallek@uni-wuppertal.de

Daniel WOLTER
Wuppertal University – Germany
daniel.wolter@uni-wuppertal.de

Nadine LUCKE
Gas- und Wärme-Institut Essen e.V.
lucke@gwi-essen.de

Jörn BENTHIN
Gas- und Wärme-Institut Essen e.V.
benthin@gwi-essen.de

## ABSTRACT

*This paper presents a methodology for the characterization of residential quarters and for their conversion into "energy cells" under consideration of the "energy cells approach"* [1]. *The primary objective of this investigation is to achieve a climate-neutral residential quarter by increasing the degree of energetic self-sufficiency using renewable energy sources and climate friendly technologies. The developed methodology is applied to a real residential quarter in Germany. The results of the application of the developed methodology are also discussed in this article.*

## INTRODUCTION

Due to the German energy transition and the associated increasing share of renewable energy sources (RES), distribution grids in particular are facing new challenges. Since the traditional electrical grids were not developed for the decentralized feed-in of fluctuating power from RES, this results commonly on voltage band violations and network equipment overloads. To avoid these problems, distribution grid operators (DSO) reinforce the grids cost-effectively in a conventional way or in special cases based on innovative solutions. The energy cells approach represents one solution for avoiding the mentioned problems on the grid by reaching an optimal local energy balance. One important consequence of the approach is the reduction of the equivalent greenhouse gas emissions of the supplied load, as RES are used for this purpose. An investigation of the application the energy cells approach to a real residential quarter is hereinafter presented.

## THE ENERGY CELLS APPROACH

The energy cells approach is one of the current research topics in Germany in the context of the energy transition (see Figure 1). The aim of the approach is to achieve an optimal energy balance within an energy cell, considering techno-economic restrictions and environmental targets. Since the main motivation for the energy transition is the achievement of climate protection goals, the energy cells approach offers a possible solution to reduce the greenhouse gas emissions through the coupling of energy sectors with a high share of RES.

A general energy cell consists of generators, converters, storage systems, consumers and connections to electricity, gas and heat distribution grids [1]. On the generation side, the focus is set on RES (photovoltaic, biogas, solar thermal, etc.). Converters for the sector coupling are e.g. electrolyzers (power to gas), electro heat pumps (power to heat) or combined heat and power units. Moreover, electricity, gas and thermal storage systems allow a temporal decoupling of energy supply and consumption within the energy cell. Industries, mobility applications, commerce and households represent the energy demand.

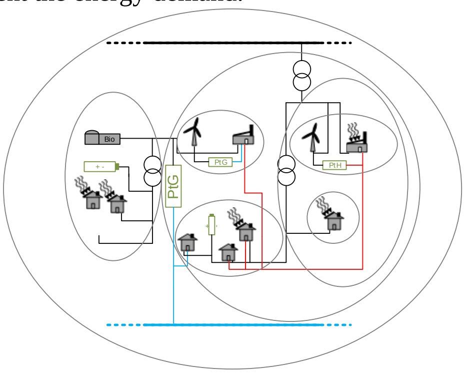


**Figure 1.** Example of a cellular energy system

## CHARACTERIZATION OF RESIDENTIAL QUARTERS

The methodology for the characterization of residential quarters is the following, in the first step, an analysis of all municipalities of the federal state of North Rhine-Westphalia (~400) is conducted [2]. The municipalities are clustered through a k-means-algorithm [3] based on the population density of their inhabited area in order to classify them as *rural*, *intermediate* or *urban* municipalities. The results from the clustering are shown in Table 1. Figure 2 illustrates the results including the cluster centers.

**Table 1.** K-means clustering results

| | Population density (hab/km²) |
|---|---|
| Rural | [2639…4075…4669] |
| Intermediate | [4727…5353…6507] |
| Urban | [6542…7674…15367] |

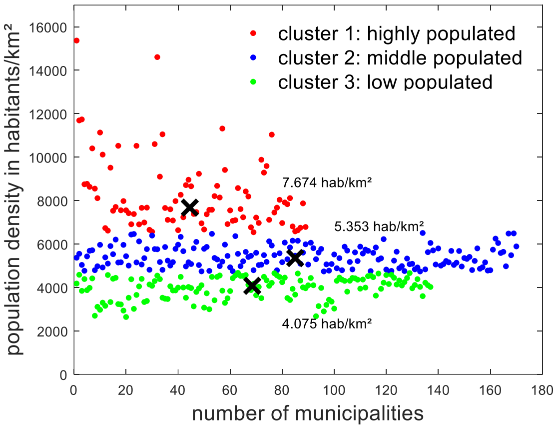


**Figure 2.** K-means clustering results

In the second step, a comprehensive analysis of the structure of the residential energy consumption and supply of the municipalities is conducted [4] [5]. This allows the assignment of reference values to the constituted clusters.
The next step in the methodology is the definition of three innovation levels: *conventional*, *intermediate* and *innovative*. The aim of these categories is to provide reference values for the technological innovation degree of a community according to the purpose of the energy cells approach. The category "conventional" is constituted by the results of the analysis of the current structure of the residential energy consumption and supply of the municipalities. Moreover, the category "innovative" specifies the parameters that would allow optimal levels of local energy generation, storage, conversion, import and export. As a result, a categorization matrix is elaborated. An example of the category "conventional" with its reference values is shown in Table 2.

**Table 2.** Reference values for the category "conventional"

| | Low populated | Middle populated | Highly populated |
|---|---|---|---|
| **Energy demand in the cell (MWh/km²/a)** | | | |
| Electricity | 7.088 | 9.312 | 13.341 |
| Heat | 35.040 | 43.800 | 74.460 |
| Gas | 108.650 | 153.256 | 221.409 |
| **Energy generation in the cell (kW/km²)** | | | |
| PV | 1436 | 1948 | 605 |
| CHP | 0 | 0 | 0 |
| **Equivalent $CO_2$-emissions generation (kg $CO_2$/kWh)** | | | |
| Power | 820 | 820 | 820 |
| Gas | 201 | 201 | 201 |
| Heat | 223 | 223 | 223 |
| **E-Mobility (%)** | | | |
| E-mob | 0 | 0 | 0 |
| **Energy storage (capacity/km²)** | | | |
| Power | 0 | 0 | 0 |
| Heat | 0 | 0 | 0 |
| **Equivalent $CO_2$-emissions (t $CO_2$/km²/a)** | | | |
| Power | 5.812 | 7.636 | 10.940 |
| Heat | 7.812 | 9.767 | 16.604 |

Since a municipality contains multiple types of residential quarters, they can be assigned to one cluster (rural, intermediate or urban) and into one innovation level (conventional, intermediate and innovative) depending on the characteristics of the quarter.

## CASE STUDY

The methodology is applied to classify a real residential quarter located within one of the analyzed municipalities. Based on the reference information of the matrix and on information provided by the local distribution network operator, the optimal energy balance within the quarter, considering all relevant restrictions, is calculated. As a result, the first steps in a way towards the transformation of the residential quarter into an innovative climate-neutral energy cell is described and the advantages of the categorization matrix are exemplified.
The overriding goal is to achieve a climate-neutral residential quarter by determining the necessary technologies for an optimal energetic self-sufficiency.

### The investigated residential quarter

The investigated residential quarter covers an area of 0,15 km² and comprises 6 streets and 184 buildings. The settlement structure can be described as heterogeneous. Primarily single-family and two-family houses and isolated small multi-family houses are found, whereby the houses have different old structures and different refurbishment structures. 595 people live in the quarter, so the population density referred to the inhabited area is 4.018 hab/km². According to the methodology presented, the quarter turns out to be low to middle populated and can be classified as a typical suburban/rural lodging residential quarter. The residential quarter is supplied by three secondary substations and connected to the gas grid via one gas pressure regulation station, which offers the possibility to couple the gas and power grids. There are just three photovoltaic systems in the quarter with an installed capacity of 13,2 kW. The photovoltaic density is very low and comes to 89 kW/km² (see Table 3). However, a large potential for PV expansion was derived from an analysis of rooftops/alignments of the houses within the quarter (approx. 1.977 kW) and of the solar radiation of the quarter's area.

**Table 3.** Energy consumption and supply in the quarter

| | |
|---|---|
| Electricity demand | 1.064 MWh/a |
| Electricity demand density | 7.090 MWh/km² |
| Heat demand | 5.955 MWh |
| Heat demand density | 39.701 MWh/km² |
| Installed PV capacity | 13,21 kW |
| PV density | 89 kW/km² |
| $CO_2$-emissions power<br>$CO_2$-emissions heat<br>$CO_2$-emissions total | 861 t/a<br>1.196 t/a<br>2.058 t/a |

The specific electrical and heat demand of the quarter comes to 7.090 MWh/km² and 39.701 MWh/km² respectively. These values show again, that the quarter can be classified as low to middle populated in the innovation category “conventional”. Furthermore, today’s equivalent $CO_2$-emissions of the quarter are high with a total value of 2.058 t/a (see Table 3). Because of these factors, there is an opportunity to design the quarter as an energy cell, improving the energetic self-sufficiency degree and reducing equivalent $CO_2$-emissions.

## Use cases

The investigation of the residential quarter is based on three *use cases*. The first two use cases are presented in this paper. All calculations are based on time series the photovoltaics (PV), e-mobility, heat and power demand (standard load profiles). The use cases are based on the assumption that the complete rooftop potential of the quarter will be equipped with PV systems. This assumption represents the best case of the generation of renewable energy within the quarter and at the same time the worst case for the power grid, which would have to handle with a huge feed-in of RES.

### Use case I

The objective of the first use case is to use the energy from the PV systems to cover the electrical load in the residential quarter considering storage systems to increase the electrical self-sufficiency on it. Thereby house batteries are implemented. In a first step, a simple energy balance between PV generation and electrical load is made in order to calculate the self-sufficiency degree without the presence of storage systems. The result shows about 30 % of electrical self-sufficiency in the mentioned conditions. In a second step, the house batteries are employ. For dimensioning the batteries, the self-sufficiency degree is calculated for different values of capacity and power of the batteries. As result, the different curves shown on Figure 3 are obtained. A set of curves is generated for every single house. Then, the area where an increase in battery capacity and power can no longer produce a significant change on the self-sufficiency degree is defined. The combination of battery capacity and power from the area are determined by selecting a real battery existing on the market considering its cost.

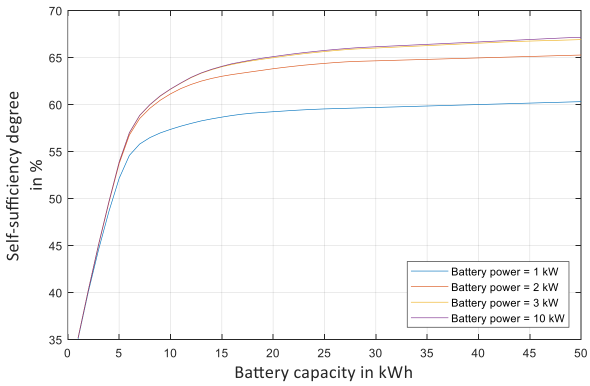


**Figure 3.** Electrical self-sufficiency degree for different battery capacities and powers for a single-family house

The curves of Figure 3 were generated for a single-family house (power consumption 4.847 kWh/a and PV capacity 5,13 kW). The figure shows that a maximum self-sufficiency degree of 67 % can be achieved with batteries with capacities up to 50 kWh and powers up to 10 kW. The optimal area to choose the battery is located between 10 kWh to 20 kWh and 2 kW to 3kW.

Figure 4 shows the electrical load curve, the PV generation, the exported and imported power to/from the grid, the state of charge (SOC) and the power for charging and discharging the battery for the single-family house of Figure 3. The figure shows that, despite the use of the battery, a considerable amount of PV power is fed into the network on days with huge generation. At days with moderate PV power generation, the battery can store the complete energy so that no power is fed into the network. At night, the power from the battery is used for covering the electrical load.

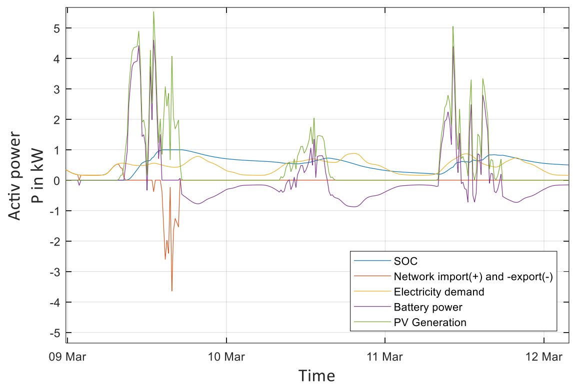


**Figure 4.** Active power for a single-family house

As mentioned, the single-family house of the example can reach an electrical self-sufficiency degree of 67 %. Depending principally on the relation between mean load and installed PV capacity, greater values can be achieved. A first calculation of the equivalent $CO_2$-emissions of the quarter shows that the use of batteries reduces the emitted $CO_2$ approximately by 149 t/a (8,2 %) from 1.807 t/a to 1.658 t/a. Therefore, the use of storage systems is a valid first step towards a climate-neutral quarter.

In a next step, the impact of the approach to the power network of the quarter is assessed. Real data of the power grid was also provided by the local distribution network operator. After doing the corresponding simulations, no voltage band violations are identified neither with nor without using the storage systems. However, the thermal current ratings are exceeded in fifty-eight events a year without using batteries (see Figure 5, base case) in the period between late April and early August. The maximum overload comes to 107,9 % of the limit value and three cables are affected by the overloads. Additionally, in the *use case I* only twenty overloads a year are identified, which represents approximately 65 % less overloads (see Figure 5, use case I). The number of overloads per line for each case is illustrated in Figure 5. It is thus shown that batteries have a positive effect on the network, reducing the level and the overall number of overloads.

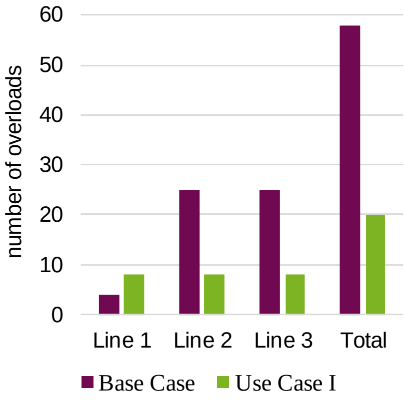


**Figure 5.** Number of overloads *base case* vs. *use case I*

**Use case II**

In the second use case, the heat demand of the quarter is taken into account. For this purpose, electrical heat pumps are investigated. Goal of the use case is to achieve a climate-neutral generation of heat by using the excess of PV generation for operating the heat pumps. The heat demand depends mainly on the external temperatures and the insulation and refurbishment of the houses. The heat pumps are selected in such a way that they can cover at least 90 % of the heat demand depending of the existence at the market and the costs. Based on historical values for the external temperature of the area of the quarter, the coefficient of performance (COP) of the heat pumps is calculated. With the COP of and the heat demand, the equivalent electrical load of the pumps is determined. This load is added to the conventional electrical load of the house and then the further procedure is identical to that in *use case I*.

The use of electrical heat pumps for covering the heat demand lead to a higher power consumption, so that the electrical self-sufficiency degree falls approximately 30 % in comparison with the *use case I* (see Table 4). But by the fact that more than 96 % of the heat demand of the quarter is covered, the energetic self-sufficiency degree (power plus heat) of the quarter comes to 82 %, which is much higher than the 9 % obtained in *use case I* (see Table 4).

**Table 4.** Self-sufficiency degrees of the quarter

| | Self-sufficiency degree | | |
|---|---|---|---|
| | **Power (%)** | **Heat (%)** | **Total (%)** |
| Today | 1,12 | 0 | 0,18 |
| PV | 30,03 | 0 | 4,55 |
| Use case I | 62,08 | 0 | 9,00 |
| Use case II | 42,71 | 96,63 | 82,03 |

**Table 5.** CO2-emissions of the quarter

| | $CO_2$-emissions | | |
|---|---|---|---|
| | **Power (t/a)** | **Heat (t/a)** | **Total (t/a)** |
| Today | 861 | 1.196 | 2.058 |
| PV | 610 | 1.196 | 1.807 |
| Use case I | 330 | 1.196 | 1.658 |
| Use case II | 1.039 | 40 | 1.084 |

Covering the heat demand using the heat pumps and the excess of PV generation has a positive impact in the overall equivalent $CO_2$-emissions of the quarter, which are 574 t/a lower than in *use case I* (see Table 5).

The results of the investigations summarized in Table 4 and Table 5 point out that the equivalent $CO_2$-emissions decrease on a case-by-case basis.

## CONCLUSION AND OUTLOOK

A methodology for the characterization of residential energy quarters is presented in this article. The application of the methodology to a real residential quarter is assessed. As first step for the transformation of the quarter into an *energy cell*, the usage of home batteries and heat pumps is investigated. The advantages of such technologies for improving the energetic self-sufficiency degree and reducing $CO_2$-emissions are demonstrated. The impact of the approach on the local power grid is also considered. Thereby a reduction in the yearly line overloads is identified. Further investigations on the quarter consider the use of combined heat and power (CHP) plants for supplying multi-family houses and the implementation of electrolyzers for balancing the remaining power generation of the quarter. Recommendations about possible business models for cellular residential quarters are being developed.

## REFERENCES

[1] Benz et al., "Der zellulare Ansatz - Grundlage einer erfolgreichen, regionenübergreifenden Energiewende," VDE - Verband der Elektrotechnik Elektronik Informationstechnik e.V. / ETG - Energietechnische Gesellschaft, 2015.

[2] Statistisches Bundesamt, "Gemeindeverzeichnis-Informationssystem GV-ISys," 2015. [Online]. Available: https://www.destatis.de/DE/ZahlenFakten/LaenderRegionen/Regionales/Gemeindeverzeichnis/Gemeindeverzeichnis.html.

[3] S. Dasgupta, Studies in Virtual Communities, Blogs, and Modern Social Networking: Measurements, Analysis, and Investigations, IGI Global, 2013.

[4] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., "Stromverbrauch im Haushalt," 2016.

[5] Bundesnetzagentur, "EEG-Registerdaten und EEG-Fördersätze," 2016. [Online]. Available: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/EEG_Registerdaten_node.html;jsessionid=EE444515C2EB3A5F6428CF8EC800F00B.