ASSESSING THE ENERGETIC SELF-SUFFICIENCY OF A RESIDENTIAL DISTRICT

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ABSTRACT

This paper presents the assessment of the energetic self-sufficiency of a residential district under consideration of the "energy cells approach" [1]. *The primary objective of this investigation is to achieve a climate-friendly residential district by increasing its degree of energetic self-sufficiency using renewable energy sources, storage systems and energy conversion technologies. The evaluation is conducted by means of a real residential district in Germany considering the repercussions of the approach on the local power grid and the economic costs.*

INTRODUCTION

The achievement of a decentralized balance between energy consumption and supply is one of the current research approaches in Germany in the context of the energy transition. For the assessment of the approach, a spatial delimited group of residential, commercial or industrial consumers (or a mix of them) is selected. Through the installation of distributed energy sources, storage systems and converters between energy sectors, the original group of consumers becomes into an *energy cell*, in which a decentralized energy balance occurs [1].

The *energy cells approach* offers solutions to reduce greenhouse gas emissions through the coupling of energy sectors with high share of renewable energy sources (RES). Therefore, the approach focuses on photovoltaic, renewable gases, solar thermal, wind etc. as energy sources. Converters for the sector coupling are e.g. electrolysers (power to gas), electro heat pumps (power to heat) or combined heat and power units. Moreover, electrical, gas and thermal storage systems allow a temporal decoupling of the energy supply and consumption within the energy cell. The approach gives as result a determined energetic self-sufficiency degree (SSD) of the energy cell as well as a specific reduction of equivalent CO_2-emissions. Objective functions of the evaluation are for instance the maximization of the SSD or the minimization of economic costs.

This investigation applies the energy cells approach to a *residential district* located in North Rhine-Westphalia.

METHODOLOGY

The investigation considers three scenarios, one for the reference year 2030 and two for the year 2050 (*trend* and *maxpv*). For the three scenarios are defined specific values for the installed renewable energy capacity –photovoltaic (PV) panels in this case– as well as for the e-mobility penetration, the power and heat demand and the renovation of buildings (see Table 1).

In order to differentiate the impact of the different technologies on the energetic self-sufficiency of the district, the investigation is based on a *base case* and three consecutive *use cases*. The *base case* considers the installation of PV panels and an increase of the power demand through the penetration of electric vehicles and a decrease of the heat demand through building renovation. For supplying the thermal demand of the district, the *base case* considers conventional oil and gas boilers.

The *use case I* adds to the evaluation the employment of battery storage systems in order to reach a time-uncoupled use of the PV energy. The *use case II* considers, in addition to the *base case* and to the *use case I*, the use of combined heat and power (CHP) systems and electric heat pumps (EHP) to supply the heat demand by replacing part of the oil and gas boilers. Finally, the *use case III* has as purpose the use of electrolysers to convert the residual PV energy into hydrogen and to inject it directly into the local gas grid. The energetic SSD of the residential district, as well as the resulting equivalent greenhouse gas emissions are calculated in every step of the evaluation and for the three scenarios in the two projection years.

THE INVESTIGATED DISTRICT

The investigated residential district covers an area of 0,15 km² and comprises 6 streets and 175 buildings. The settlement structure can be described as heterogeneous. Primarily single-family and two-family houses and isolated small multi-family houses are identified, whereby the houses have different refurbishment structures. About 595 people live in the district, so the population density referred to the inhabited area is 4.018 hab/km². According to [2], the district turns out to be low to middle populated and can be classified as a typical suburban residential district. The district is supplied by three secondary substations and is connected to the gas grid via one gas pressure regulation station, which offers the possibility to couple the gas with the power grid through an electrolyser. Currently there are only three PV systems in the district with an installed capacity of 13,2 kW. However, a large potential for PV installation is derived from an analysis of rooftops/alignments of the houses within the district and of the solar radiation of the district's area (approx. 1.893 kW_p). The electrical and heat demand of the district comes to 995 MWh/a and 4.043 MWh/a respectively. Furthermore, today's equivalent CO_2-emissions of the district amounts to a total value of 1.887 t/a.

INPUT DATA AND TECHNOLOGIES' SIZING

The assessment of the energetic self-sufficiency of the district uses a MATLAB model that simulates the employment of different technologies by using time series with a time resolution of fifteen minutes for a period of one year for every scenario and use case. Table 1 shows the assumed values for the installed PV capacity and e-mobility for the considered scenarios. It shows also the assumed building renovation rates as well as the resulting specific CO_2-emissions for the energy sources. The heating structure of the residential buildings is also shown on the table.

Table 1. Assumed values per scenario

	Today	**2030**	**2050 trend**	**2050 maxpv**
Photovoltaic [kW]	13,2	406	681	1.893
E-mobility [%] E-mobility [autos]	0 0	17 57	30 101	70 235
Building renovation rate [%/a]	-	1 (until 2030)	2 (from 2030)	
CO_2-emissions [kg_{CO2}/kWh]				
Power mix Gas mix Oil	0,535 0,201 0,271	0,219 0,152 0,271	0,005 0,076 0,271	
Buildings with heating systems				
Oil (Low temp.) Gas (Low temp.) CHP EHP	35 140 - -	30 128 9 8	21 78 26 50	

All of the mentioned boundary conditions are defined for the reference years 2030 and 2050. The specific emission factors are based on further assumptions for the global energy supply and the energy mix in Germany deduced from an analyses of different scenarios used currently in Germany [3] [4]. The prospective heating structure results from the analyses of the current building ages in the residential district and the assumed renovation rate.

The sizing of the different technologies and the production of the time series for the simulation are explained in the following sections.

Electrical load

Time series for the electrical load were generated with an algorithm that assigns the load of typical electrical devices to the residential households based on statistical information and on the probability for using such devices. Aspects such as the season of the year, the type of day, the daytime and the number of inhabitants were taken into account in the time series generation. The results were matched with information of the total electricity demand of the buildings provided by the local distribution system operator.

Heat load

Information of the currently district's thermal demand was provided by the distribution system operator. The thermal demand for the reference years 2030 and 2050 considers the relative demand reduction for typical building refurbishments of similar reference buildings from [5]. Time series for the heat load were generated considering the different heating technologies. For buildings with CHP systems, the VDI reference load profiles from [6] were used. In order to avoid an unrealistic addition of heat peaks, the profiles were time shifted (maximum ±1 h) following a normal distribution. Time series of buildings with EHP were generated using the VDN standard load profile method for interruptible appliances based on data published by local distribution system operator. All other time series were generated using standard load profiles H0 [7]. The energy demand for warming water was determined using information from [6].

Photovoltaics

Time series for photovoltaics were generated by means of an algorithm that considers weather data, the roofs' pitch of the buildings, the azimuth angle and the district's location on earth. Weather data from 2000 to 2015 was used to obtain a typical mean weather year. The PV panels were random distributed in the district according to the roofs' size [8].

Batteries

Batteries are dimensioned separately for every building of the district that has gotten an energy generation unit (PV panel or CHP). A battery follows equations (1) and (2) for the charging and discharging process respectively.

$$SOC(t) = SOC(t-1)(1-\sigma) + \frac{P(t)\Delta t \eta_c}{C_{max}} \quad (1)$$

$$SOC(t) = SOC(t-1)(1-\sigma) - \frac{P(t)\Delta t}{\eta_d C_{max}} \quad (2)$$

$SOC(t)$ is the state of charge after t; σ is the self-discharge per hour; $P(t)$ is the charge or discharge power in t; Δt is the length of t; η_c and η_d are the charge and discharge efficiencies, respectively; C_{max} is the maximum capacity of the battery.

The electrical SSD of every building is calculated for different values of battery capacity and power. As result, a set of curves battery capacity vs. SSD for the different battery powers is generated. Then, the area where an increase in battery capacity and power can no longer produce a significant change on the SSD is defined. The dimensioned battery capacity and power are determined by selecting a real battery existing on the market that matches with the selected area of curves. This process is also explained in [2]. The assumed main battery parameters are a maximum power of 4,6 kW and a Capacity of 13,5 kWh.

E-mobility

Time series for the electrical vehicles are generated considering the battery parameters and the vehicles' usage. The charging and discharging process of the batteries are described by equations (1) and (2). The vehicles' usage considers data from the statistical use of vehicles by people in Germany along different type of days [9]. The assumed battery parameters are a capacity of 40 kWh and a consumption rate of 14.5 kWh/100 km, which matches the average of today's sold cars [10]. The maximum battery power comes to 11 kW, which represents the typical maximum charging power in residential areas. A yearly vehicle's mileage of 14.000 km/a was assumed according to the German mean [11]. The charging simultaneity of the vehicles was assumed according to [9]. The electrical vehicles were random distributed in the district according to number of buildings' inhabitants.

Combined heat and power

Since the CHP costs are particularly high for micro CHP systems, only buildings with high heat demand were furnished with CHP. Suitable CHP were selected from systems available on the market. The achievement of a high amount of full load hours (about 6.000 h) in a heat guided operation mode was considered. In case the power generation from CHP excesses the power demand or it cannot be stored by the batteries, the CHP are throttled or switched off completely. In the last case, CHP's auxiliary burner supplies the heat load.

Electrical heat pumps

All considered EHP achieve an annual coefficient of performance (COP) of 3,8 which is the minimum required to qualify for German subsidies [12]. To achieve high efficiency the EHP are combined with floor heating and only placed in renovated buildings with moderate heat demand and sufficient garden area for installing the EHP's ground collectors.

Electrolysers

Electrolysers are dimensioned considering a maximization of the full load hours while still being able to convert a reasonable amount of the PV energy surplus using ordered annual residual load duration curves. The assumed electrolyser efficiency comes to 70 % and the nominal electrolyser powers are between 50 kW and 200 kW.

ELECTRICAL SELF-SUFFICIENCY

The simulation model calculates the buildings' exported or imported power in every time step. This power is the result of the balance between the generated, the consumed and the stored power in every building. The electrical self-sufficiency of the district is obtained after considering the exported and imported power by all buildings in a whole year. The electrical SSD is obtained with the equation (3). E_{el_d} is the total electrical energy demand of the district; E_{el_i} is district's imported electrical energy.

$$SSD_{el} = 1 - \frac{E_{el\_i}}{E_{el\_d}} \tag{3}$$

Figure 1 shows the electrical SSD of the district for the different scenarios and use cases. The *base case* shows electrical SSDs from 24,5 % to 38,3 % along the scenarios. The more PV capacity installed in the district, the higher the self-supply of it. This happens despite the increasing e-mobility penetration.

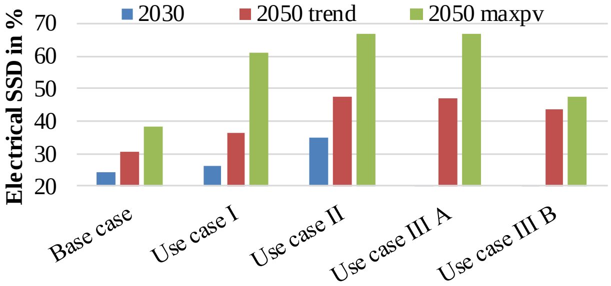

Figure 1. Electrical self-sufficiency degrees of the district

The use cases I to III are compared with the *base case* in order to identify the effect of the added technologies. The *use case I*, which adds home batteries to the evaluation, shows an improvement of the electrical SSDs of the district. The *scenario 2050 maxpv* demonstrates the potential of the electrical storage: district's electrical SSD rises from 38,3 % to 61,1 % (about 23 percentage points). Home batteries follow in the simulation an operation strategy that shifts batteries' charging start time to the middle of the day at summer months of the year. This strategy allows the attenuation of most of residual PV peaks in summer, reaching a relieve of the power grid.

The *use case II* shows the additional effect of the combined installation of CHP and EHP. Both technologies follow a heat guided operation strategy. EHP represent in this way an additional electrical load in the simulation and CHP an additional power source. With the *use case II*, the electrical SSD of the district rises by about 9 % to 11 % in the scenarios *2030* and *2050 trend*.

The *use case III* adds an electrolyser to the assessment and is divided in two additional cases (A and B). Purpose of the electrolyser is the conversion of the residual electrical power generated in the district into hydrogen. It is assumed that the produced hydrogen is injected directly into the local gas distribution grid. The *use case III A* adds the electrolyser to the simulation maintaining the same technologies of the *use case II* (PV, e-mobility, batteries, CHP and EHP). Therefore, the electrical SSDs between those use cases experience only marginal changes. The *use case III B* takes batteries out of the consideration in order to identify the effect of the absence of electrical storage on the full load hours of the electrolyser. As a consequence, the effect of CHP and EHP on the electrical SSD without electrical storage is also identified: CHP increases the electrical SSD by about 13 percentage points in *scenario 2050 trend* and 9 percentage points in *scenario 2050 maxpv* in comparison to the *base case*. The use of an electrolyser does not affect the electrical SSD due to the assumed operation strategy for it. The *Use Case III* is intentionally not investigated in the *scenario 2030*.

The electrical SSDs shown in Figure 1 get round the fact that the primary energy required for the additional power generation from CHP –in the use cases II and III– comes mainly from imported gas from the local gas distribution grid. In order to consider this fact, the district's energetic SSDs are analyzed in the following section.

ENERGETIC SELF-SUFFICIENCY

An analysis of the district's energetic SSD considers the electrical and thermal demand together. The thermal demand of the district is positively affected by the assumed building renovation rate, which reduces the heat demand in the different scenarios (see Table 1). In the *base case* and the *use case I*, only gas and oil boilers are considered for supplying the thermal demand of the district. This takes today's district situation as starting point. The *use cases II* and *III* consider CHP and EHP for covering the heat demand by replacing part of the conventional gas and oil boilers (see Table 1). A district's energetic SSD can be obtained through the equation (4). E_{el_d} is the total electrical energy demand of the district; E_{th_d} is the total thermal energy demand; E_{el_g} is the renewable electrical energy that is generated and consumed within the district; E_{th_d} is the renewable thermal energy that is generated and consumed within the district.

$$SSD_{en} = \frac{E_{el\_g} + E_{th\_g}}{E_{el\_d}+E_{th\_d}} \qquad (4)$$

The renewable electrical energy generation within the district consists of PV energy and of electricity from reconverted hydrogen from the CHP. The residual PV energy used by the electrolyser to produce hydrogen is in this way not included in E_{el_g} but only the reconverted amount of energy. The renewable thermal energy generation consists of heat from the environment extracted by the EHP as well as from heat generated from hydrogen.

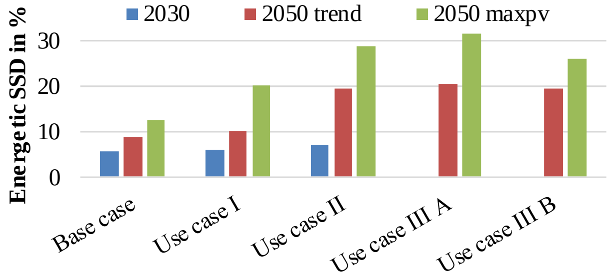

Figure 2. Energetic self-sufficiency degrees of the district

Figure 2 shows the energetic SSDs of the district for the different use cases and scenarios. The maximal energetic SSD comes to 31,7 % on the *use case III A* in the *scenario 2050 maxpv*. The energetic SSDs of the *base case* and the *use case I* are lower in comparison with the other use cases due to the absence of EHP and electrolysers in those cases.

AVOIDED EQUIVALENT CO$_2$-EMISSIONS

The equivalent CO$_2$-emissions of the district are considered related to district's original conditions projected for the corresponding scenarios. The results are summarized in Figure 3. The avoidance of CO$_2$-emissions increases with the consecutive measures of the use cases and with the expansion of PV according to the scenarios. In the medium term, CO$_2$-emissions can be reduced by up to 30 % due to the use of batteries and innovative heat systems. In the *scenario 2050 trend*, 56 % to 60 % of the equivalent CO$_2$-emissions can be avoided. If the penetration of PV is maximized along with an increasing use of e-mobility, the avoidance of emissions in 2050 rises about 16 percentage points. Furthermore, the results of the analysis show the effect of the single measures and of the overall concept in connection with the external boundary conditions. The differences between the use cases within the same scenario are comparatively low. It follows therefore that the majority of avoided CO$_2$-emissions results from the positive development of the global energy supply and particularly from the assumed high share of RES in the electricity generation of Germany.

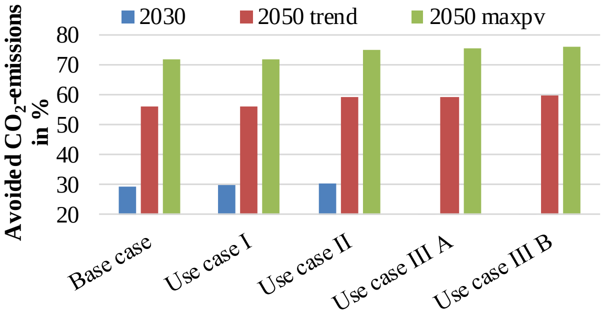

Figure 3. Avoided equivalent CO$_2$-emissions of the district

IMPACT ON THE POWER GRID

The local distribution system operator provided real data of the power grid. Conventional power flow calculations are conducted using time series from the MATLAB model with a time resolution of one hour for a period of one year for every scenario and use case. Figure 4 shows the *number of limits violations* per year, which contains both the amount of voltage violations and the amount of transformer and line overloads. The *scenario 2030* shows no voltage violations or overloads in the power grid. The *scenario 2050 trend* shows a maximum of 156 limits violations/a in the *base case*. This amount is reduced to 36 limits violations/a in the *use case I* due to the positive effect of the batteries on the attenuation of the residual PV peaks. In the *use case II* the number of limits violations rises to 99 /a because of the CHP penetration, which brings additional decentralized voltage elevations. Finally, the number of limits violations is held back by the operation of the electrolysers in the *use case III* relieving the power grid. The same behavior is observed in the *scenario 2050 maxpv* for a higher amount of limits violations, which comes for instance to 1.753 /a in the *base case*. The critical time of the year for the power grid is, as expected, between late April and early August due to the PV energy surplus.

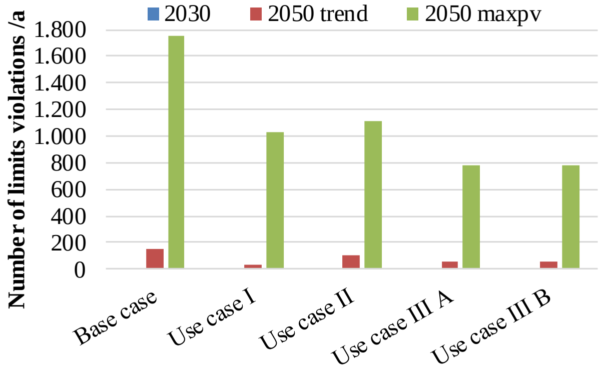

Figure 4. Number of electrical limits violations

ECONOMIC EVALUATION

The economic evaluation of the assessment uses the known *present value method*. It is assumed that the implementation of the use cases is made in two steps: with a first investment on the year 2030 and a second investment on the year 2050. The fact that two scenarios are considered for the year 2050 allows the comparison between *transformation paths* (*trend* and *maxpv*). *The present values* are given for the year 2030 as "present time" of the calculation. The CAPEX include the cost of all technologies as well as the needed power grid reinforcement to avoid electrical limits violations and the costs for building renovation and underfloor heating –necessary for the EHP. The OPEX include the electricity, gas, oil and diesel costs as well as maintenance costs and the profit from the PV surplus. The evaluation compares all use cases' costs with the costs of implementing none of the use cases on the district and determines the savings. The obtained values are shown on Figure 5.

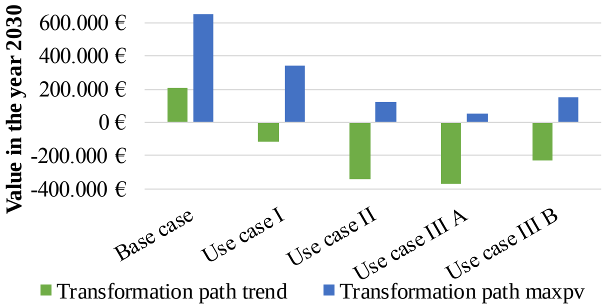

Figure 5. Value of the use cases in the year 2030

The values of the *transformation path trend* show no economic viability except for the *base case*. In contrast, the *transformation path maxpv* shows viability for all the evaluated cases, where the *base case* is again the best investment followed by the *use case I*.

CONCLUSIONS

This investigation assesses the self-sufficiency (SSD) of a residential district by evaluating several use cases and scenarios. The paper shows how by means of the combined installation of energy generators, converters and storages and considering building renovation and increasing e-mobility, it is possible to achieve electrical SSDs from up to 67 % and energetic SSDs from up to 31,7 % in the investigated district. A consequence of the approach is the avoidance of equivalent CO_2-emissions from up to 76 % in comparison with the equivalent CO_2-emissions in case of implementing none of the use cases on the district. The economic evaluation of the approach show high economic potential for high PV and e-mobility penetration; the additional use of batteries would be the next better option.

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