Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

Assessing pathways to carbon neutrality in a neighbourhood study in Germany

To cite this article: Miaomiao He *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 082010

Assessing pathways to carbon neutrality in a neighbourhood study in Germany

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Abstract. Neighbourhoods are becoming more and more important for the success of the energy transition and achieving the climate protection goals. This paper describes results from a case study of a typical residential neighbourhood in Germany, in which investigation of pathways to climate neutrality has been carried out. Both technical potential and challenge under the current legal framework are presented. The aims are to answer questions such as to what extent and in what sequence the energy-related emissions of an existing neighbourhood can be reduced in the long term through further integration of photovoltaics, low-carbon technology, thermal storage and, if necessary, building refurbishment. Two pathways are exanimated: in the gas pathway by using CHP units with biogas and in the electricity pathway by electrifying the heat demand through the use of heat pumps. Three scenarios are defined for both pathways, which differ in particular by the level of building refurbishment, PV generation, supply temperatures in the heating network and uptake of electric vehicles.

1. Introduction

With the increasing interconnection of sectors of transport, buildings and energy supply, the complexity of decision paths increases enormously, and consequently presents building and neighbourhood owners with fundamental new challenges. The specific initial situations, the requirements for implementation, and the embedding of the subarea in the overall system must be analysed and optimized, in order to achieve several conflicting targets such as climate protection, economic efficiency, security of supply and social consensus [1].

In the following, the results of a short case study of neighbourhood in Regensburg in Germany are described. Investigations were carried out to identify which pathways exist in principle for designing a climate-neutral neighbourhood, how high the economic benefits are, and which legal hurdles and challenges arise at the present time due to the structures that have grown up in the energy transition and volatile energy prices.

2. The Alfons-Bayerer-Strasse neighbourhood

The Alfons-Bayerer-Strasse (ABS) quarter is a purely residential quarter in the west of the city of Regensburg and offers 342 apartments for approx. 880 residents in 10 multi-family houses (MFH, approx. 18,000 m^2 of living space) and a high-rise building (HRB, approx. 6,500 m^2 of living space). 270 apartments (approx. 18,800 m^2) are owned by a municipal housing association (HA), 72 apartments (approx. 5,600 m^2) are privately owned. All buildings were constructed in the mid-1960s. While the privately owned MFH are still largely in the efficiency standard from the year of construction, with the exception of the replacement of windows and the subsequent insulation of the top floor ceiling, the MFH owned by the HA were already retrofitted in terms of energy efficiency in 2011. The HRB was extended in 2022 to meet fire protection requirements and underwent comprehensive building energy retrofitting.

The heat supply for space heating and, in part, also hot water is provided in the neighbourhood via a central heating network powered by a condensing boiler (rated output approx. 895 kW) and a low-temperature boiler (rated output 875 kW) in the basement of the HRB with a flow temperature of approx. 75 °C. In the privately owned MFH, hot water is produced decentrally via electric instantaneous water heaters. In the MFH and HRB owned by HA, rooftop solar systems currently support water heating (Figure 2). In all MFH, heat is transferred via radiators; in the HRB, underfloor heating was installed as part of the 2022 energy retrofitting. A 2-pipe system brings heat for heating and hot water with a flow temperature of 55 °C to the transfer stations of the apartments.

Figure 1. Aerial view of the ABS neighbourhood (google map)

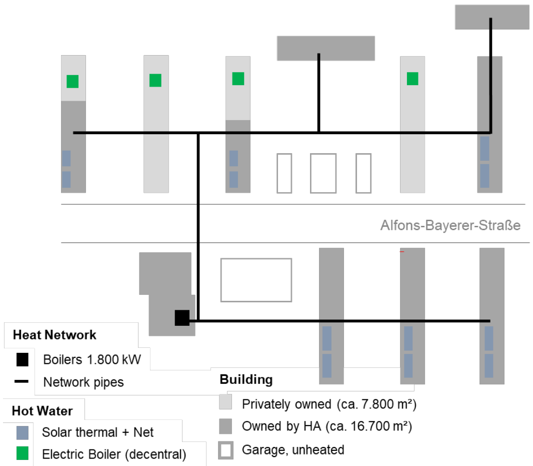

Figure 2. Distribution of building ownership and heat network in the neighbourhood

The extension and refurbishment of the HRB in the neighbourhood offered the opportunity for an extensive integration of photovoltaics into an architecturally appealing overall concept. The question arose as to the potential of PV on the roofs and facades and what technical, economic and legal opportunities and obstacles exist in the implementation of the integrated energy transition by coupling the sectors of heat, electricity and mobility. In addition, questions arose whether an energy system in the neighbourhood to achieve the goal of climate neutrality can be implemented without improving the energy efficiency of the buildings, and if not, to what extent the buildings need to be retrofitted to achieve the goal. Finally, what would be the most economical solutions given the current fluctuating energy prices.

3. Methodology

In the legal analysis, relevant environment administrative law is presented, followed by an overview of the energy-related challenges for the neighbourhood owner, e.g. due to grid regulation regulations, tax and reporting obligations. Finally, possible subsidies are presented as well as their effects on the economic viability of different electricity marketing and purchase models.

In the technical analysis, the transformation potentials to a climate-neutral neighbourhood were investigated, which consist of increasing integration of renewable energies, the conversion of heat supply and the energy efficiency of buildings. With the focus on the CO_2 reduction potentials in the neighbourhood, various heat generation technologies were investigated as examples to cover the heat demand, or transform the heat demand to electricity demand, which are supplemented by photovoltaic modules on roof and facade surfaces.

3.1. Legal analysis

A major challenge for the energy transition at the neighbourhood level is that no legal framework exists to date that enables the local exchange of electricity among end consumers in the neighbourhood while using the general electricity grid. The subsidy structure of the EEG [2] and KWKG [3] is not in line with the legal framework for energy and grid management. Thus, it is impossible to obtain subsidies for the tenant electricity model (electricity is generated by PV modules on the building or CHP and supplied directly to the tenants of the building or neighbourhood buildings), if the public general grid is used. But, even in private possession of the owner of the neighbourhood, a grid can only be regarded as not public if it comes under the definition of a so-called customer installation ('Kundenanlage') according to Section 3 No. 24 a) EnWG, which is quite narrow. If the neighbourhood buildings are interconnected in order to maximize the increase of energy efficiency, the electricity cables required for this purpose in the neighbourhood will be regarded as part of the general public grid, according to the previous case law of the BGH. Therefore, in order to obtain subsidies, the buildings must not be interconnected.

As to economic viability, due to the subsidy of the EEG and KWKG, the tenant electricity model is most economical viable, especially with the continuously rising electricity price. Still, in the case of the tenant electricity model, the neighbourhood owner in principle becomes the energy supplier and must therefore submit to the obligations of the EnWG and other laws, which is quite demanding. It is possible that a legal framework will be established which will overcome the shown obstacles for a maximized interconnection and distributed energy supply through the implementation of the RED II directive, however this is still partially pending [4].

3.2. Technical analysis

To simulate possible development paths, the entire area of ABS is mapped in a simulation model. In this, the relevant energy flows (demand and generation) are simulated in hourly resolution to balance the intermittent renewable energy supply with the variable energy demand in the neighbourhood. The modelling inputs and parameters are listed in the following subsections.

3.3. Buildings

According to the heating consumption values available from 2020, the buildings of the neighbourhood are roughly divided into three groups (see Table 1). In order to simplify the simulation of the neighbourhood's energy demand, three building models are created accordingly using thermodynamic simulation to represent the three building groups with the corresponding building envelopes and U-values, so that the predicted heat consumptions correspond to the actual values.

Table 1. A summary of three categorised building groups in the neighbourhood.

Category	Number of Apartments	Heated Area	Space Heating Consumption	DHW Consumption	Space Heating Consumption per Area
	[-]	[m^2]	[MWh/a]	[MWh/a]	[$kWh/m^2.a$]
HRB	98	6,458	195	117	30
MFH_retrofitted	128	10,163	515	332	51
MFH_unretrofitted	116	7,814	690	27	88
Total	342	24,435	1,400	476	-

For future developments, it is assumed that all buildings will reach the efficiency standard that was currently achieved when the HRB was refurbished (Effizienzhaus 55/GEG 2022). To achieve this, the building envelopes of the MFH that are still in their original condition from the 1960s must be completely refurbished; for the MFH buildings that were already refurbished in 2012, further efficiency improvements are necessary, e.g., in the future replacement of windows and through additional insulation of the top floor ceiling. In a further efficiency level, it is assumed that almost all efficiency measures on the building envelopes are implemented and that the heating demand of the buildings is further reduced according to the passive house standard (Passivhaus/GEG 2022).

The household electricity demand is calculated on the basis of typical daily electricity profiles published by the German Association of Energy and Water Industries (BDEW) [5], resulting in a total demand of 737 MWh/a (30 kWh/m^2.a) for the neighbourhood. This demand remains the same in all modelled scenarios, as no intervention of reducing the household electricity is considered.

3.4. PV generation and electric mobility

Three stages of PV generation are considered: For stage I, a usable PV area of 2245 m² is envisaged, which counts the facade of the HRB and the roofs of the MFH owned by the housing association. For stage II, it is assumed that further areas such as roofs of garages and bicycle parking spaces etc. are equipped with PV. This results in an area of 3025 m². For stage III, all available roof areas, including the roofs of privately owned buildings, are taken into account, resulting in an area of 4670 m².

With the increasing uptakes of electric vehicles, a growing electricity demand from electric mobility must also be considered within sector-coupling of the neighbourhood. Again, two levels of uptakes of electric vehicles (EV) are considered. The calculation of the number of EVs is based on the number of inhabitants in the neighbourhood, resulting in an uptake of 58 EVs at level I, and 110 at level II, which corresponds to an electricity demand of 82 MWh/a and 150 MWh/a, respectively.

3.5. Transformation pathways and scenarios

Two transformation pathways for the energy system are investigated in the neighbourhood:

- cogeneration by combined heat and power plants (CHP) fuelled by biogas
- electrification of the heat demand by using heat pumps

In each of the pathway, three scenarios are considered (see table 2). The assessment of CO_2 emission from the energy used within the neighbourhood is calculated on the basis of the CO_2 equivalent factor of final energy defined in DIN V 18599-1:2018-09 [6]. Upstream process chains outside the neighbourhood are also taken into account in the extraction, conversion and distribution of the fuels or substances used in each case.

Table 2. Description of three scenarios

	Scenario I	Scenario II	Scenario III
Buildings	space heating demand approx. 60 kWh/m^2.a	space heating demand approx. 30 kWh/m^2.a	space heating demand approx. 15 kWh/m^2.a
Photovoltaics	449 kWp, 405 MWh/a	605 kWp, 557 MWh/a	934 kWp, 851 MWh/a
Heat Network	supply Temp. 65 °C	supply Temp. 55 °C	supply Temp. 45 °C
Electric Vehicle	58 EVs, 82 MWh/a	110 EVs, 150 MWh/a	110 EVs, 150 MWh/a

4. Results

4.1. Heating energy demand reduction

Important steps toward minimizing energy requirements in the neighbourhood were already taken with the building energy retrofitting carried out by the HA on the MFH up to 2012. This was continued with the extension and retrofitting of the HRB in 2022. Figure 3 shows the absolute space heating demand of all buildings before and since the first refurbishment in 2012 for the entire neighbourhood. The efficiency level of Effizienzhaus 55/GEG 2022 is labelled "from 2030", as it is assumed that the implementation of the energy refurbishment will be completed by 2030. The alternative efficiency level of Passivhaus/GEG is designated "from 2030a". It is important to notice that, as there is not only no reduction in the DHW and household electricity demand, but also an increase of EV demand, the proportion of the space heating demand over the energy demand of the whole neighbourhood drops significantly, from 52% “from 2022”, to 35% “from 2030” and 21% “from 2030a”.

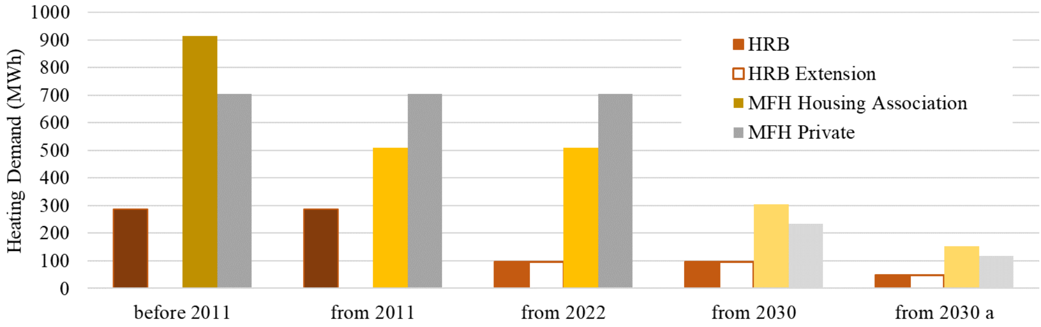

Figure 3. Absolute heating demand in different refurbishment steps in the neighbourhood.

4.2. Cogeneration using CHP – 'Gas Pathway'

The CO_2 emission of the 'gas pathway' of the three scenarios defined in table 2 is shown in figure 4. The results are presented in a step-wise accumulated way, which means the emission of each labelled measure has taken into account the measures implemented before it. For example, the emission labelled 'CHP' counts for all the measures before, which include 'Building Retrofit', 'Photovoltaics' and 'Electric Vehicles'. In scenario I, where there is no demand reduction through building retrofit, 77% of CO2 reduction can be achieved; in scenario II 88%; and in scenario III, the emission is negative, which means there is more energy generated in the neighbourhood than it is consumed, and therefore achieving the goal of climate neutrality. One advantage of replacing the existing boilers by a CHP unit fueled by biogas is that the high supply temperature of the heat network can be maintained, and the indoor comfort temperature can be guaranteed in all existing buildings without the need for further refurbishment. However, on a national level, only a certain proportion of the current natural gas demand can be substituted with biogas.

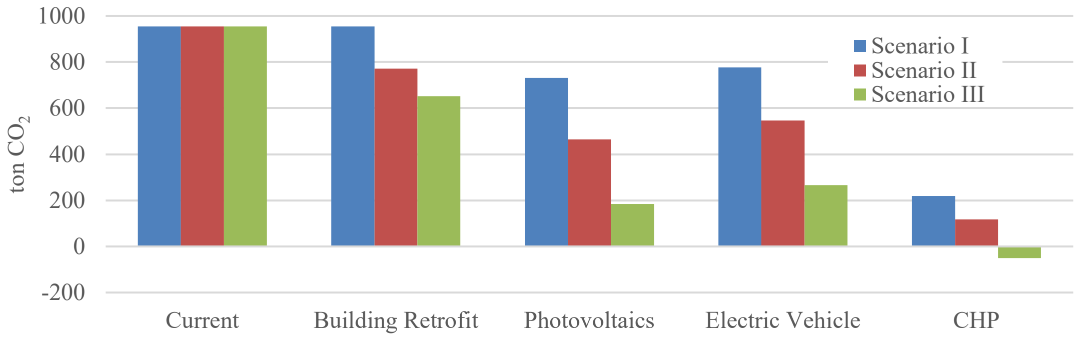

Figure 4. CO_2 emission in the 'gas-pathway' for all three scenarios.

4.3. Electrification using Heat Pumps – 'Electricity Pathway'

Similarly, the step-wise accumulated CO_2 emission in the electricity pathway is shown in figure 5. In scenario I, 51% of reduction can be achieved, which is significantly lower than the 77% of reduction in the gas pathway. This is due to the higher supply temperature of the heat network required (65 °C) to maintain the comfort room temperature in the non-refurbished MFH, which results in a low seasonal coefficient of performance (COP) of the heat pumps. In scenario II, with refurbished MFH and lower supply temperature (55 °C), the seasonal COP of the heat pumps increases significantly, resulting in a much higher increase of emission reduction up to 75%. A reduction of 97% can be achieved with the buildings of passive house standard and low supply temperature of 45 °C. However, extra measures need to be taken to ensure there is no legionella risk in the domestic hot water provision. Interestingly, without further building refurbishment, either pathway could reach the goal of climate neutrality.

In addition, finding a suitable heat source for the installation of heat pumps in an existing neighbourhood is challenging. Normally air source heat pumps would be out of the question due to the associated noise at this level of capacity. Permission of using ground water could be restricted, and available roof area for solar thermal collectors is limited. Extracting the heat from the ground, by either horizontal or vertical heat exchangers, in an existing neighbourhood, is nearly impossible, due to the limited open ground surface available and the level of disruption caused by drilling.

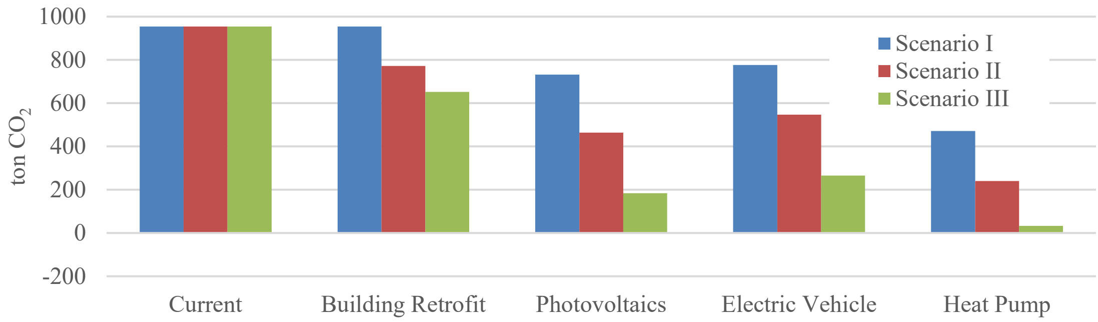

Figure 5 CO_2 emission reduction in 'electricity pathway' for all three variants.

5. Discussion & conclusion

Interestingly, without building energy retrofitting (scenario I), both 'gas' and 'electricity' pathways could not achieve the goal of climate neutrality. Even with moderate retrofitting to Effizienzhaus 55 (scenario II), this goal still could not be reached. Climate neutrality could only be achieved or nearly achieved in scenario III with the extensive building energy retrofitting to Passivhaus standard. However, the implementation of the retrofitting measures required in scenarios III would be highly challenging due to the mixed ownerships of the buildings and the associated high costs. Moreover, it would not be economical to implement the pathways without the establishment of a legal framework which allows maximized interconnection and distributed energy supply in neighbourhoods.

In this study, building energy retrofitting was considered for the space heating demand reduction of the neighbourhood. With the decrease of the space heating demand, DHW and household electricity dominate the energy demand (scenario II and III). As the DHW and household electricity demand are largely associated with the number of households, for a neighbourhood such as the ABS neighbourhood in this study, with relatively higher density of population and smaller surfaces for PV installation, to cover the energy demand completely with onsite generated renewable energy is very challenging.

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