Peter Klement, Patrik Schönfeldt, Lucas Schmeling

3 Multi-Objective Design Optimisation of District Energy Supply – The Influence of Different Domestic Hot Water Concepts

Summary: The supply of districts with electricity and heat can be designed in a variety of ways. This concerns the technical building equipment on the one hand and the sizing and operational management of energy-generating and energy-storing systems on the other hand. We used the "Model Template for Residential Energy Supply Systems" (MTRESS) to simulate and optimise supply concepts with respect to energy costs, CO_2 emissions, and own-consumption using the example of the Helleheide neighbourhood. In the study, district heating network supply concepts based on 80 °C for direct domestic hot water supply, 40 °C with reheating for water treatment and legionella prevention and 40 °C without reheating but on-demand heat exchangers or ultra-filtration are compared. We find that most optimal solutions strongly integrate the heat supply with the electricity sector, with solar thermal supply being an exception to this general trend. Furthermore, operation and sizing of energy supply systems can have a bigger impact on both emissions and total costs than the actual choice of the technologies.

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Abbreviations

CHP combined heat and power plant
COP coefficient of performance
DHI diffuse horizontal irradiance
DHW domestic hot water
DNI direct normal irradiance
ENaQ Energetic Neighbourhood Quarter (German: Energetisches Nachbarschafts Quartier)
GT geothermal
GHG green house gas
HP heat pump
KPI key performance indicator
PV photovoltaics
P2H power to heat
SH space heating
ST solar thermal
WT wind turbine

3.1 Introduction

Nowadays, energy supply systems not only have to provide energy, but energy must be provided at the lowest possible cost with minimal emissions. This results in the requirement that energy systems must be optimized with respect to several criteria. If these requirements cannot be fulfilled optimally at the same time, solution spaces arise, e.g., in the form of Pareto fronts, where the solution cannot be improved with respect to one criterion without at least one other criterion deteriorating.

For the energy supply, different technologies with different dimensions and in possible different combinations are usually available as options. Simulations of individual supply solutions usually involve a lot of effort. Therefore, the decision which technology combination in which dimensioning is to be used is usually made via simulation and comparison of individual scenarios. An optimization over many technologies and designs is therefore rarely carried out. Usually, only the costs for the energy supply are decisive. The avoidance of emissions follows in a downstream consideration when solutions with similar costs are compared. The aim of this paper is to present a concept in which energy system proposals are developed that are based on many technologies and in which the comparability of solutions with respect to various criteria is clearly visible.

Since the percentage of energy required for the provision of domestic hot water (DHW) in residential buildings continues to rise in line with the insulation standard (Zeisberger 2017), various supply concepts are currently under investigation (Energiewendebauen 2022).[1] From an energy point of view, there is always the desire to bring the supply temperatures as close as possible to the user temperatures to have to add as little cold water as possible. This increases the possibilities to supply DHW from renewable energy in an energy-efficient way. On the other hand, according to § 4 of the Drinking Water Ordinance,[2] it is a legal requirement in Germany how the quality and health safety of DHW must be ensured, e.g. with regard to legionella. Usually, this is ensured at the expense of energy efficiency by having to provide possible tap temperatures of minimum 60 °C at least for centralised DHW supply (DIN 1988–200:2012-05). The discussion about future possibilities to supply DHW is currently ongoing and being researched. Therefore, we would like to demonstrate our methodology by comparing conceivable concepts. There are various options to secure the quality of DHW especially with respect to legionella. An overview can be found in (Yang/ Li/Svendsen 2016). Here, we consider three options of DHW supply for demonstrating our concept:

S. 1	with flow temperatures at 80 °C,
S. 2	with flow temperatures at 40 °C, with legionella protection via on-demand heat exchangers or ultrafiltration.
S. 3	with flow temperatures at 40 °C with electrical reheating by flat for legionella protection.

One (S. 1) is heat supply well above 60 °C. To safely maintain this level at any place of the DHW plumbing system, we aim for a design flow temperature of 80 °C at the heating central. Alternatively, the temperature of the heat grid can be reduced to a level sufficient for space heating. We assume constant 40 °C at the heating central. As legionella population grows at that level, DHW cannot be stored. Instead, it is either heated on demand using heat exchangers (40 °C for both space heating (SH) and DHW, S. 2) or heated further using electric heating (DHW supply at 60 °C, S. 3), which according to (Völker/Kistemann 2015) is the minimum for safe hot drinking water storage. To model latter concept, the heat demand for DHW is reduced but electricity demand is added. Similar concepts for reduced heat network temperature have been investigated by (Toffanin/Curti/Barbato 2021). However, they rely on a micro booster heat pump instead of an electric boiler.

The three concepts were not made available for free optimization by the underlying technology selection because the decision is probably made because of considerations not part of the optimisation (i.e. legal concerns). Further, there is no inherent order in the choice of DHW supply solutions: While a pure choice of the temperature level would offer a common scale, so the decision about DHW solutions is of binary nature, leading to distinct optimisation problems anyway.

1 Research Project: EnOB: ULTRA-F – Ultrafiltration als Element der Energieeffizienz in der Trinkwasserhygiene, FKZ 03ET1617.

2 Verordnung über die Qualität von Wasser für den menschlichen Gebrauch (Trinkwasserverordnung – TrinkwV).

The methodology is explained in 3.2, whereas boundary conditions for the simulations are described in 3.3. The input data are presented at 3.4 and the results are shown in 3.5. A summary is given in 3.6.

3.2 Methodology

3.2.1 Goals and indicators

The basic concept of targeting and therefore deciding on a common objective between stakeholders was described by (Schmeling/Schönfeldt/Klement et al. 2020) from the Energetic Neighborhood Quarter (German: Energetisches Nachbarschafts Quartier, ENaQ) point of view. Specifically, the project partners, consisting of a company operating as a housing association, a university focusing on participation, a research institute dealing with renewable energy concepts, the local municipality, and companies from the energy and IT sectors, participated in the process. The involved persons took over different point of views as described by (Schmeling/Schönfeldt/Klement et al. 2020). The result is a catalogue of indicators, which can measure the effects of the ENaQ project, within the physical infrastructure, the participation process, the digital platform, and the project itself. The indicators chosen for the physical infrastructure focus on the energy system and the mobility. Due to the lack of partners who could directly and actively contribute to mobility solutions, sector-integrated energy concepts that include mobility had to be neglected. This article therefore focuses on the electricity and heat supply of a residential neighbourhood in the context of a sector integrating approach. The main goals therefore are:

- low greenhouse gas emissions,
- low costs,
- low exergy losses,
- high share of renewable energy,
- enabling of sector integration,
- high own-consumption and high self-sufficiency quota,
- high grid serviceability, and
- low vulnerability and high resilience.

As a consequence, the topics resource consumption, costs and energy supply were identified as main concerns for the physical infrastructure.

In this context, energy supply must be seen in the light of the aspects of own-consumption quota, self-sufficiency quota, share of renewable energies, electrification of transport and heat, grid efficiency and local energy trading. The goal of the ENaQ project is local energy trading among neighbours, so that local energy supply is the focus and externalization of resource procurement is to be explicitly reduced, but not completely avoided. In other words, the goal is to create a neighbourhood that relies as much as possible on own-consumption, but is not completely self-sufficient or entirely independent of an external grid. The neighbourhood may very well relay on an external grid.

Each of the topics resource consumption, costs and energy supply can be described by several indicators that are commonly and readily used to quantify the characteristics of energy supply systems in neighbourhoods. As an example, for the topic of resource consumption, GHG emissions, electricity consumption, heat consumption as well as relative exergy consumption, building energy consumption and e.g. land sealing can be mentioned. The indicators in general should be recorded for the district in the future in order to compare the district with other districts.

To optimize the energy system, emissions, costs and own-consumption were selected as key performance indicator (KPI) from the previously determined indicators. The background for this choice of KPIs is that they are intended to span a solution space that maps stakeholder concerns (Schmeling/Schönfeldt/Klement et al. 2020). In this way, conflicting requirements in particular are to be considered. Correlating indicators do not open any new dimensions and do not contribute substantially to gaining knowledge; on the contrary, they may lead to unnecessary consumption of resources when optimizing the energy system. The remaining indicators that were not selected as KPIs were consequently neglected for optimization.

While the definition of costs and own-consumption was relatively straightforward, various options where discussed about the aspect of emissions attributed to grid electricity. Consistency requires that grid supply and feed-in have the same absolute value, as electricity passing through the area does neither cause nor prevent emissions. To facilitate transferability, the (time dependent) emission factor of the electricity mix is considered. Other choices, i.e., the last power plant in the merit order, would have caused inconsistencies when being applied to many local energy systems at once. Details on the actual calculation of the KPIs were published by (Wehkamp/Schmeling/Vorspel et al. 2020) and (Schmeling/Schönfeldt/Klement et al. 2020).

3.2.2 Pareto-Optimization of Energy Systems

With defined goals and connected indicators, there are two options regarding optimization. One option would be to agree on one outstanding KPI which is then used for optimisation. This also might be a newly formulated compound KPI that integrates weighted indicators into one. Multi-objective optimisation marks the second option. It allows for late weighting by picking one of many pareto-optimal design options. However, it increases the computational effort. To tackle this, the operation of the possible energy systems was split into a separate, linear optimisation. This optimisation is purely economic and just minimizes operational costs, modelling a possible commercial operator. A schematic of the concept and a set of example results are displayed in Figure 3.1. The detailed procedure for optimisation can be found in (Schmeling/Schönfeldt/Klement et al. 2022).

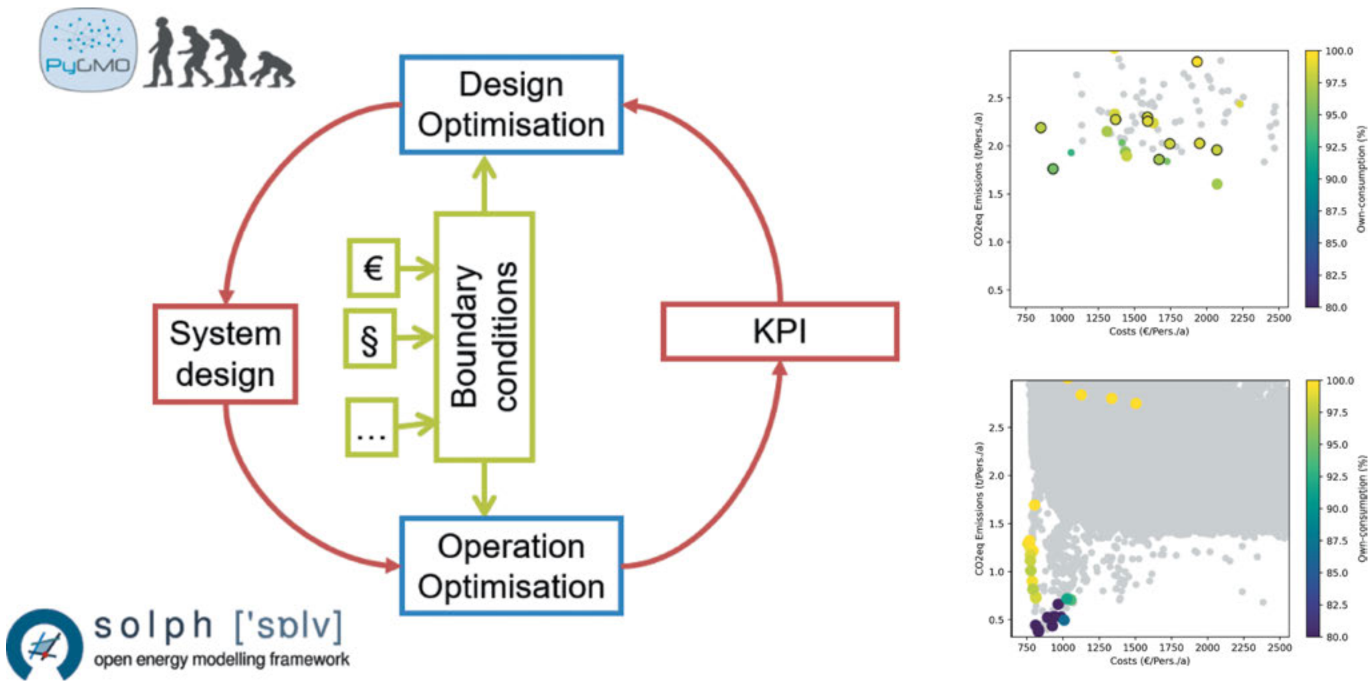

Figure 3.1: Schematic process of energy system optimization (left) and example Pareto-optimal systems after initialization (top right) and after optimization (bottom right). In the results, every dot marks a possible system design, the coloured ones are pareto-optimal.

The selection and design of the supply concept cannot be made purely based on technical requirements and certainly not without considering several boundary conditions. These will therefore be briefly outlined below.

3.3 Boundary Conditions

3.3.1 Legal Boundary Conditions

Since the energy supply concept under development is planned to be realised and operated, the current German legal framework conditions must be mapped as accurately as possible. This applies, of course, to laws on the supply of energy to private individuals, but also, for example, to the funding of renewable energies.

Another important point are the taxes and levies to be paid. These are usually independent of the distance between the producer and the consumer.[3] This would make it economically unattractive to produce and consume energy on site. A solution is to set up a customer system (Kundenanlage[4]). The customer system is not part of the public grid[5] and is only connected to the public grid at one point. The district then forms a single unit that can operate as a cohesive unit with respect to the public grid. For electricity generated and consumed within this customer system, only the EEG (German Renewable Energy Sources Act) levy, which is charged to refinance the funding of renewable energies, must be paid. Grid fees and taxes do not apply. More details on this topic can be found at (Brandt/ Schmeling/deBronstein et al. 2021, Katic/Schmeling 2022).

Likewise important for the design of the energy concept are minimum requirements for the energy supply of buildings, which in Germany are bundled in the GEG (Gebäudeenergiegesetz – Building Energy Act). On the one hand, this sets an upper limit for the primary energy factor of the energy supply and the transmission heat coefficient of the building envelope based on the technical standard (DIN V 18599:2018–09 2018). While the latter is determined purely by the building and therefore cannot be influenced by us, the primary energy factor can be significantly influenced by a more efficient, renewable energy system, which may make it possible to obtain higher subsidies. The GEG also specifies a minimum level of renewable energy to be used for heat supply, which can usually be achieved with solar thermal energy, or alternatively using heat pumps (HPs), combined heat and power plant (CHP) units, or pellet boilers, for example.

3 § 17 Nr. 1 StromNEV (Stromnetzentgeltverordnung – Electricity Grid Charges Ordinance).

4 § 3 Nr. 24a EnWG (Energiewirtschaftsgesetz – Energy Industry Act).

5 § 3 Nr. 17 EnWG.

3.3.2 Economic Boundary Conditions

The economic boundary conditions include, on the one hand, external conditions, e.g. especially related to the energy industry, and, on the other hand, internal conditions, such as the business models used. The external economic boundary conditions are largely dependent on the legal framework outlined in the previous chapter, as the energy industry is strongly regulated due to its (partly) natural monopoly. The use of external electricity markets is particularly important for the design of the energy concept. These are described in detail for Germany by (Klement/Brandt/Schmeling et al. 2022). We assume here that the neighbourhood obtains all its electricity on the day-ahead market and sells surplus electricity on this market if legally necessary.

The fact that the district acts as a single player in this market is possible due to the customer system. The organisation of this is done by a new market player, the district aggregator. In addition, this aggregator establishes local energy trading among neighbours, i.e., it allows electricity to flow between different participants within the neighbourhood without having to face too high legal, bureaucratic and organisational hurdles. More details on the neighbourhood aggregator can be found at (Brandt/Schmeling/de-Bronstein et al. 2021, Katic/Schmeling 2022).

3.3.3 Technical Boundary Conditions

The planned district consists of seven buildings that will be connected to a district heat network with a central heat supply. A sketch of the energy system design is depicted in Figure 3.2. The model has been released as open-source software (Schönfeldt/Schmeling/Wehkamp 2021).

To have redundant heat supply in case a combined heat and power plant (CHP) must be maintained, the investor requested that gas boiler, pellet boiler, and HP are sized large enough to fulfil the peak demand

$$\max(P_{\text{demand, th}}) \leq P_{\text{gas boiler}} + P_{\text{pellet boiler}} + P_{\text{heat pump}}. \tag{3.1}$$

This way, shortages or reliance on power to heat (P2H) can be excluded even in case of unplanned operation conditions.

3.4 Input Data

The subsequent simulation is based on calculating and evaluating the behaviour of the energy system in an hourly resolution. For this reason, it is necessary to model the temporally variable boundary conditions as (at least) hourly time series. To be able to trace the later simulation results back to their influence, the relevant time se-

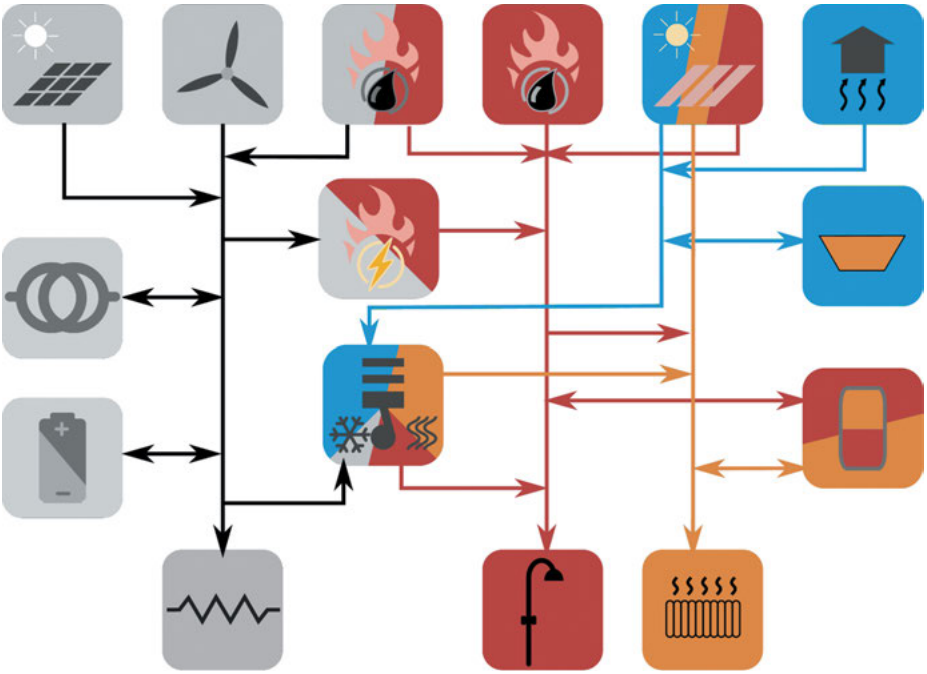

Figure 3.2: Graph of the energy system template including all considered technologies. The icons represent (left to right, top to bottom) photovoltaics (PV), wind turbine (WT), CHP, boiler, solar thermal (ST), ambient heat, grid electricity, power to heat (P2H), seasonal storage, battery, heat pump (HP), warm water storage, electricity demand, domestic hot water (DHW) demand, and space heating (SH) demand.

ries and their origins are to be explained. Both external boundary conditions, which can be divided into environment and market, and internal boundary conditions, i.e. the energy demand of the buildings, are relevant.

It is important to use data from one common year, as many of the variables influence each other. For example, it would be mistaken to combine meteorological data from one year, electricity market data from another and electricity demand data from a third, as these are all interconnected. Various factors must be considered when selecting the relevant year. On the one hand, the year should be as current as possible to have realistic market prices. Secondly, the year should contain a cold period so that the energy supply will work under these conditions. After extensive research, we decided on the year 2017.

3.4.1 External Conditions – Meteorology

A decisive factor for the energy demand of buildings, but also for the generation of renewable energies, is the weather. Various parameters come into play in this context. It is possible to obtain this data either as measured data from a nearby weather station or as a numerical weather prediction, i.e. interpolation of a weather model. Due to data quality and availability, we use freely data from the nearest weather station of the German Weather Service (DWD). This is located at the airport in Bremen, approx. 43 km east of the neighbourhood. The location is in the same climate zone and can therefore be used without restrictions.

Relevant meteorological variables are the outdoor temperature, e.g. for the heat demand of the buildings or the efficiency of a PV system, the direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) for the yields of the photovoltaics (PV) system, the ground temperature for the efficiency of a geothermal heat pump (HP) and the wind speed for the yield of the wind turbine (WT). The greatest impact is exerted by the air temperature and the two radiation time series, which are shown in Figure 3.3.

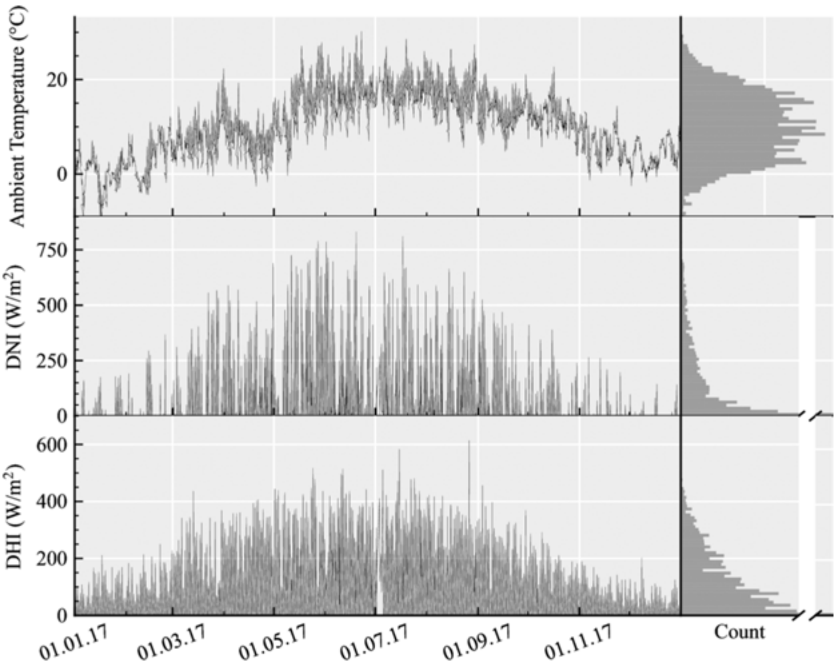

Figure 3.3: Visualization of the most relevant meteorological time series for the optimization and simulation of the energy system.
(Source: Deutscher Wetterdienst (DWD))

3.4.2 External Conditions – Grid Electricity

As already mentioned in 3.3, the district electricity market interacts directly with the national day-ahead market by buying missing energy and selling excess energy. Figure 3.4 shows the time course of prices on this market.

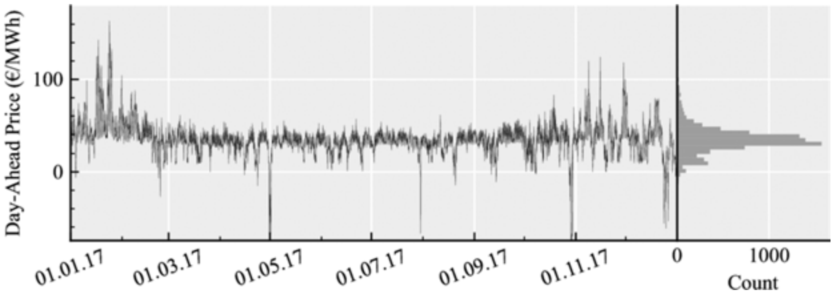

Figure 3.4: Visualisation of the electricity price of the day-ahead market for the DE-LU bidding zone. (Source: ENTSO-E Transparency Platform)

In addition, there are of course, depending on legal requirements, taxes and levies, which in total are significantly higher than these pure energy purchase costs.

The procurement of electricity available at this market is of course also associated with climate-damaging emissions, as fossil-fuel power plants are still operated extensively here. It is important to note that the composition of the electricity mix changes permanently due to volatile renewable energies. This does not only happen locally, but in the entire European interconnected grid. With the help of a flow tracing algorithm (Bialek 1996, Hörsch/Schäfer/Becker et al. 2018), the electricity flows and proportional shares can be broken down and transferred based on technology-specific emission factors to a temporally resolved electricity mix of the German market (Windmeier 2019). The time series of the intensities of electricity procurement can be seen in Figure 3.5.

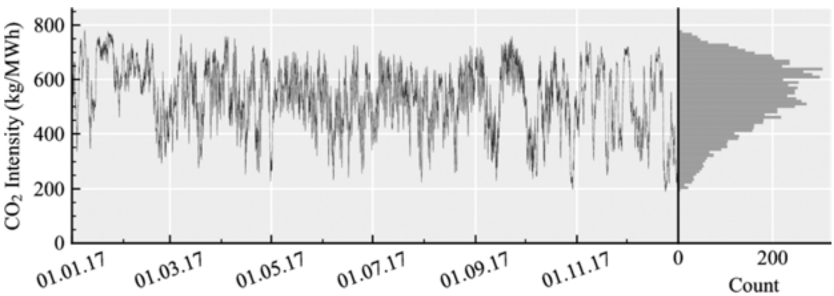

Figure 3.5: Visualisation of the CO_2 intensity of the mean German electricity mix, determined with the help of a flow-tracing approach from ENTSO-E Transparency Platform data.

Another relevant aspect is how the market costs and the associated emissions are linked. For this purpose, the correlation of the two time series can be seen in Figure 3.6. Both correlate positively with each other, linearly in the primary region. This is mainly due to the subsidies for renewable energies in Germany, in which large plants are no longer subsidised on a flat-rate basis, but their electricity must be marketed on the stock exchange. As these electricity volumes are usually generated in larger quantities due to meteorological dependency, this leads to a shift in the supply curve and thus to a reduction in prices. In contrast to other areas of life, purely economically oriented action thus usually has a positive ecological impact.

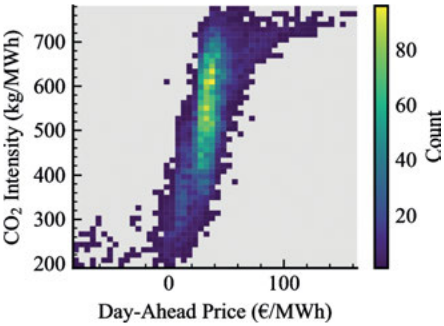

Figure 3.6: Visualisation of the correlation between electricity market prices (Figure 3.4) and CO_2 intensities (Figure 3.5) as a 2D histogram.

3.4.3 Energy Demands

To match the energy system to the building to be supplied, their energy demand must be determined, as well as the temporal course of this demand.

The electricity demand is the easiest to determine, as it is largely dependent on the occupants and their behaviour. Assumptions were made regarding the resident structure, household size, age and employment status based on similar objects in the real estate developer's portfolio. With the help of the LoadProfileGenerator (Pflugradt/Muntwyler 2017), a software tool for creating synthetic load profiles based on a behavioural simulation, these structures were translated into an hourly load profile of the entire neighbourhood. The result can be seen in Figure 3.7.

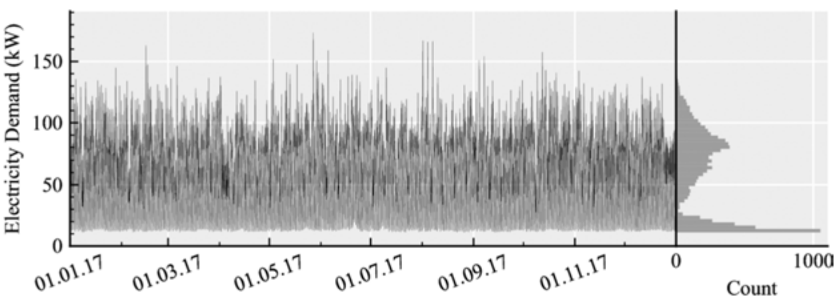

Figure 3.7: Visualisation of the electricity demand of the district.

Using the same methodology and the same tool, the DHW demand was determined, which can be seen in Figure 3.8. This demand is initially stated here in litres and must later be translated into different thermal or electrical demands for DHW production, depending on the DHW concept.

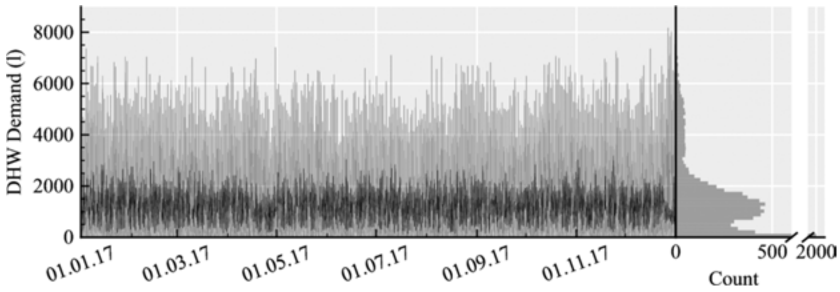

Figure 3.8: Visualisation of the DHW demand of the district.

The space heating (SH) demand of buildings is more difficult to determine, as it depends not only on user behaviour but also on building physics. With the help of the software QuaSi (Technical University of Braunschweig – Institute for Building Services et al. 2020), simplified cubatures, building material properties, weather data and usage profiles were defined for each building to simulate the buildings energetic behaviour and thereby create hourly load profiles for SH using a generic thermal building model based on EnergyPlus® (Crawley/Pedersen/Lawrie et al. 2000). These were compared to the annual heat demand according to energy performance certificates following (DIN 4108–6 2003) and scaled accordingly. However, since part of the SH demand does not have to be covered by the heating system, but instead is covered by internal gains from electricity usage, the electricity demand time series was subtracted from the previous SH time series, which, of course, can never be less than zero. This results in the time series of the SH demand of the buildings shown in Figure 3.9.

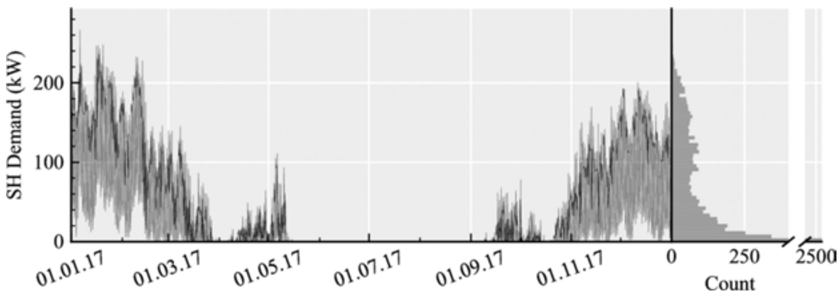

Figure 3.9: Visualisation of the SH demand of the district.

The SH and DHW requirements of the buildings have so far only been determined for each building individually. However, as there will only be one central heating system, the heat will have to be distributed via a district heating network. This is associated with heat losses that the energy system must provide in addition to the actual demand. These losses are determined according to a methodology described by (Vorspel/Bücker 2021, Wehkamp/ Schmeling/Vorspel et al. 2020) and thus results in the heat time series to be provided at the outlet of the central heating system. To keep the grid losses low, it helps to operate the grid at as low a temperature as possible. This is especially possible if the DHW concept realises legionella-free conditions in another way. Figure 3.10 therefore shows the heat demand at the outlet of the heating centre for a heating network at 40 °C and 80 °C flow temperature.

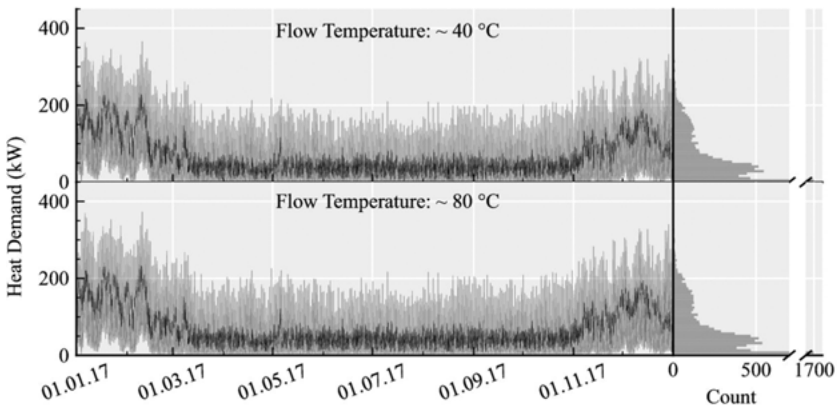

Figure 3.10: Visualisation of the heat demand of the district, as it is to be provided from the heating centre, for different temperatures of the heating network. On average, the higher temperature increases the losses, and thus the demand by 5 %.

3.5 Results

As the demands are almost constant over the three concepts, it is expected that they can reach similar combinations for costs and emissions. While this is particularly true for the minimum emissions that can be reached (0.5 t/Pers/a) and because additional investment can significantly reduce emissions until this minimum is reached, the costs significantly deviate (cheap: 550 EUR/Pers/a to 600 EUR/Pers/a, low emissions: 650 EUR/Pers/a to 800 EUR/Pers/a).

An overview of the pareto-optimal solutions is displayed in Figure 3.11. It shows that most solutions strongly integrate the heat supply with the electricity sector, using CHP or HP. We observe three groups of solutions: For all three DHW supply options, the lowest emissions are achieved if the electricity grid is avoided as much as possible at expensive and therefore high-emission times. As electricity fed into the grid can balance for negative emissions (Figure 3.5), the solutions featuring the lowest emission all focus on CHPs. A further reduction of the emissions is not possible without increased production of electricity, thus the available area for PV and the heat demand (via demand for heat covered by a CHP) define the lower end of the emissions. This also explains why a slightly higher demand in the 80 °C scenario does not come as a disadvantage for these solutions. It should be noted that this strategy can only work if CHP electricity has lower emissions than grid electricity (Klement/Brandt/Schemling et al. 2022).

Solutions with emissions between 1.0 t/a and 1.5 t/a are dominantly supplied using geothermal (GT) and ST. The latter is the most relevant heat supply technology that is not coupled with the electricity sector. However, solutions with GT or ST heat sources seem not to be competitive under the assumed conditions if DHW temperature cannot be supplied by the heat network. While these supply options mark the compromise between costs and emissions in the other two DHW treatment options, electrical boosters mostly drive them out from the space of pareto-optimal solutions. Boilers (both, gas and pellet) do not account for most of the heat in any of the energy system designs, still they serve as backup in these GT and ST options. Gas boilers, however, provide about half of the heat in more traditional CHP concepts which mark the low-cost/high-emission end of the scale in Figure 3.11.

At this point, it should be noted that the requirement of redundancy as described in Eq. 1 is not optimally chosen. As the operation is optimised purely economically, installed gas boilers would be used not only as a backup. Consequently, the heuristics found solutions with the lowest emissions when building pellet boilers or heat pumps as backup devices. In the concept S. 3, the solution with big HP do not use these with a GT source, instead they serve as power-to-heat (with a coefficient of performance (COP) of 1). This can be seen as there are HPs without geothermal coverage. On the other hand, pellet boilers are never used but just chosen to fulfil Eq. 1 without having a gas boiler. This fact shows that the role of the heat sector as a provider of flexibility in the electricity sector cannot be emphasised too much.

The presented results suggest that the principle advantages and disadvantages of supply technologies are not fundamentally different for the investigated temperature levels. A higher temperature increases costs, especially of the solutions based on heat-pumps, but they remain pareto-optimal. On the other hand, increased electricity demand due electric heating of DHW becomes a problem for heat pumps, if they compete for the same (local) renewable electricity.

It should be noted that these results were obtained for new buildings with a rather high population density. We expect the situation to be different, i.e. when more local renewable energies are available per person or the influence of DHW on the overall heat demand is reduced.

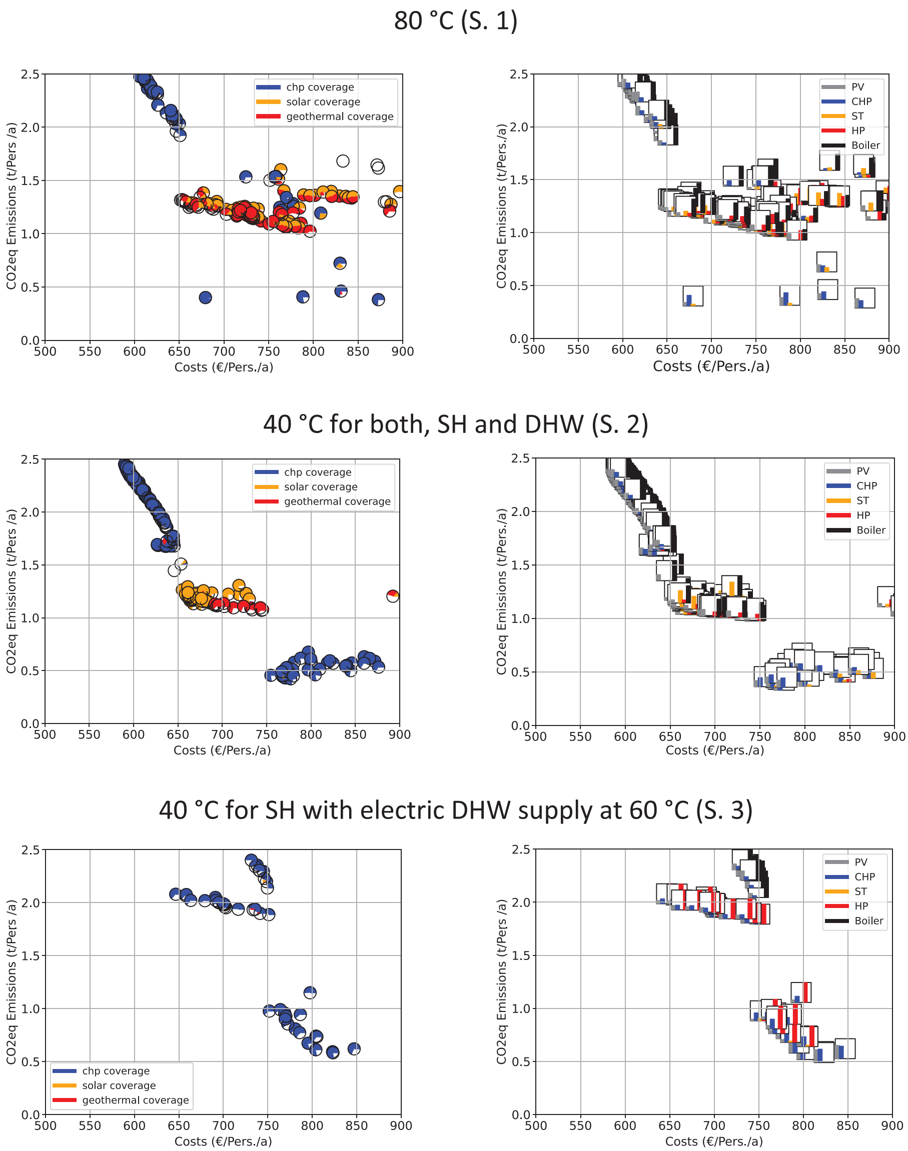

Figure 3.11: Left: Contributions of different heat supply technologies to the total demand. The white areas represent heat covered by either gas boiler (if present) or power to heat. Right: Size of generation technologies. The size of the bars is relative to the maximum size (PV: 500 kW, CHP: 150 kW (electric), ST: 415 m^2, HP and boiler: 670 kW). Own-consumption increases from the lower left hand side to the upper right hand side. It is not displayed explicitly because most solutions reach quotas of at least 70%, which is also the reason why pareto-optimal solutions in the upper right-hand corner are rare (cf. Figure 3.1, which shows S. 3).

3.6 Summary

We presented a concept for energy system design for the ENaQ project that simultaneously optimises indicators representing the interests of different stakeholders. We find that flexibility in the heating sector is a key for low emissions. Regular operation of gas boilers must be avoided. Furthermore, we compared three centralised DHW supply concepts, finding that rising the temperature electrically eliminates solutions relying on GT or ST.

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