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STUDY

MODELING SECTOR-INTEGRATED ENERGY SUPPLY IN DISTRICTS

Investigation of the advantages of optimizing energy systems at the district level compared to optimization at the building level

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This publication is issued on behalf of the Federal Ministry for Economic Affairs and Climate Action. The German Energy Agency (dena) assists the Federal Government in various projects to implement the energy and climate targets in the context of the energy transition.

Climate-neutral districts and areas

Districts are becoming more and more important to the success of the energy transition and are increasingly playing a key role. Many threads come together here: The key factors are transportation, buildings and energy supply. This gives rise to a variety of synergies in particular. In cities and municipalities, it is expedient to consider not only individual buildings, but also the building within its full spatial context. This opens up completely new potential for efficiency and options for action at the local and regional levels.

Districts are interfaces. They are the meeting points for many things that have historically grown differently and, above all, as separate systems. At the same time, districts offer a wide range of options for the climate neutrality that is desirable both politically and socially —along with many advantages. For example, local renewable energy or efficiency potential can be harnessed, systems and storage units can be designed, positioned and operated optimally, different demand profiles can be balanced out and the spatial efficiency of the entire district can be increased.

The work of the German Energy Agency (dena) in the district action area aims to contribute to the broad implementation of district-based concepts. In this regard, dena has identified the following fields of action:

- Improving the regulatory framework
- Analyzing technologies and concepts
- Strengthening processes and business models
- Highlighting German and international best practices
- Forging connections among stakeholders
- Implementing pilot projects

The study titled **"Modeling sector-integrated energy supply in districts"** is part of a **series of publications on the subject of districts** published by dena. This study examines the advantages of integrated optimization of energy systems at the level of entire districts rather than individual buildings.

Further publications on this topic of focus include (only available in German):

- Study: **"Das Quartier – Teil 1: Überblick über die gesetzlichen Rahmenbedingungen und Förderrichtlinien für die Energieversorgung von Gebäuden im räumlichen Zusammenhang"** (The district — part 1: Overview of the legal framework and funding guidelines for supplying energy to buildings in a spatial context)
- Study: **"Das Quartier – Teil 2: Analyse des Zusammenspiels und Aufzeigen von Schwachstellen"** (The district — part 2: Analysis of interactions and identification of vulnerabilities)
- Study: **"Thermische Energiespeicher für Quartiere"** (Thermal energy storage for districts)
- Project report: **"Klimaneutrale Quartiere und Areale"** (Climate-neutral districts and areas)
- Fact sheets: **"Fokusthemen"** (Focus topics)
- Fact sheets: **"Quartiers- und Arealkategorien"** (District categories)
- Fact sheets: **"Praxisbeispiele"** (Practical examples)

Contents

1 Executive Summary

This study investigated the benefits of integrated optimization of energy systems at the district level rather than the individual building level. Although supplying heat to entire districts is increasingly under consideration, electricity systems with local generation for self-supply purposes have so far only been optimized at the building level due to regulatory conditions. District-based optimization, in which electricity and heat can be exchanged between buildings within a given district and electricity and heat systems are considered and optimized in combination, is not yet possible due to the existing regulatory framework.

In order to quantify the advantages of district optimization, the study's authors carried out model calculations in which the exchange of electricity and heat is possible locally at no cost and compared how the resulting district-optimized energy system differs from an energy system in which each building is optimized individually and the district energy system is created by aggregating the individual systems. However, a neutral comparison poses a challenge, as different supply options are possible at the district level than at the individual building level (e.g., biogas CHP, purchasing wind power by means of a bilateral power purchase agreement (PPA) or use of waste heat) and as districts can differ greatly in terms of structure (e.g., rural/urban, residential/mixed areas). Furthermore, although the costs of supplying energy to individual buildings can be readily determined, the current lack of a regulatory framework renders it difficult to estimate the possible additional costs of operation and any grid fees, taxes and levies associated with supplying energy to entire districts, which has not yet been practiced with the exception of heating grids.

In order to factor in the main influences on district energy systems and at the same time keep the number of calculation variants manageable, four district types were defined. The types differ in terms of three criteria: urban/rural, new construction/renovation and residential/mixed-use area. District-related optimization calculations were carried out for each one for two cases: free exchange of electricity and heat within the district, and planning related to individual buildings. The researchers also included an intermediate variant in which electricity can be exchanged, but no central heat supply is possible. This results in 12 variants, for each of which a sector-coupled model was prepared using the KomMod energy system model and the cost-optimal overall solution was calculated.

The results show that district-optimized supply has significant economic advantages over individual building supply if there is sufficient heat demand density. Rural areas with low density of heat demand are the only places where the advantage lies not with district-optimized supply in general, but rather district-optimized power supply with heat being supplied to individual buildings, as a heating network cannot be operated economically in these circumstances. The cost advantages for district-optimized supply to non-rural districts amount to between 31 and 45 percent. The reasons for this clear cost advantage lie in an increased level of self-sufficiency with low-cost, locally generated renewable energy in the case of a district supply, along with access to additional supply options. However, it should be noted that only the energy production costs were calculated. Additional costs associated with operating the electricity grid within the district were not taken into account, nor were any taxes and/or levies that may apply, as it has not yet been possible to estimate these due to the lack of a regulatory framework and practical examples. Nevertheless, it is safe to assume that although the cost advantages will be lower in reality, they do still exist, and that the comparisons between district types are not influenced by this, either.

As this demonstrates that district solutions signify an advantage for the introduction of decentralized renewable energy and thus the transformation of the energy system, it is advisable to strengthen them. This requires, in particular, evolutionary steps in the regulatory framework, as this is the only way to actually unlock these economic advantages locally. This can take the form of extending the regulations on customer installations under the German Energy Industry Act (Energiewirtschaftsgesetz, EnWG) to include districts or designing the legal framework accordingly when introducing renewable energy communities in accordance with the EU Renewable Energy Directive (RED II) (European Union, 2018), which should be transposed into German law as soon as possible.

2 Introduction

Climate-neutral energy systems are based (largely) on renewable energy, which is characterized by a high degree of decentralization. This will allow cities and municipalities to generate a relevant proportion of their own energy in the future, supplying themselves. Rooftop solar potential in urban areas will need to be tapped to achieve climate targets, as it is available without additional use of land and as installations in other areas, especially open spaces, often compete with other uses. In addition, generating electricity close to where it is consumed reduces transportation costs.

The energy system of the future will feature a high degree of electrification, and thus strong links between the electricity, heating, cooling and mobility sectors. It will be highly dynamic due to the fluctuating generation of solar and wind energy and will therefore increasingly integrate electrical, thermal and gas storage systems. Intelligent energy management will enable efficient operation that also creates synergies through the exchange of energy volumes at the local level.

Development of climate-neutral energy system structures calls for new planning methods. In the past, which was dominated by fossil fuels, electricity was generated in centralized power plants and merely distributed locally. To date, fossil fuels have dominated the heat supply, accounting for over 80 percent, with heat being generated primarily on a decentralized basis in individual buildings. Local and district heating play only a secondary role, as does electricity-based heat supply. This means that responsibility for planning, investing in and operating heat generation systems has rested chiefly with individual building owners to date. Decarbonization is expected to increase the proportion of heating networks, particularly in cities with high building and energy demand density, as this is the only way to tap into the heating potential of geothermal energy and waste heat. An additional advantage of these networks is that biomass and waste can be burned efficiently and with low emissions in combined heat and power (CHP) plants. Heating networks also hold potential for harnessing solar thermal energy to a greater extent, beyond simply heating drinking water in summer.

In the electricity sector, it is expected that solar power will be generated on most building roofs, interim energy storage in the form of batteries will bring greater self-sufficiency for buildings and districts alike, the controlled charging and discharging of electric vehicles (EVs) will become a relevant factor in the operation of distribution grids, the conversion of excess electricity into heat will further boost system efficiency, and demand will be adjusted to the availability of electricity to a certain extent. This will require today's local electricity distribution system to evolve into a local marketplace for the exchange of electricity with the aim of high self-sufficiency and low costs, combined with new business models such as those that will also be offered by local energy communities in the future. The shift away from fossil and nuclear energy sources and toward renewables will therefore also lead to new energy system structures that require changes in energy planning.

Local energy planning for climate-neutral districts and cities pursues the goal of using an optimal mix of local generation sources and energy conversion and storage technologies to achieve a secure and cost-effective energy supply with the highest possible proportion of locally generated renewable energy and waste heat. It would be advantageous if the local energy system with its remaining energy imports and exports behaved as efficiently as possible as part of the overall system and was able to provide flexibility to the upstream energy system. This requires integrated planning of the local energy system, taking into account the dynamics of generation and consumption, sector coupling, energy storage for different time periods, demand-side management, bidirectional charging of EVs and intelligent operation.

However, this also means **that in the future, centralized national and regional planning of the electricity system and building-centric heat planning will be supplemented by integrated energy system planning at the district or local level as a third planning level** (see figure 1).

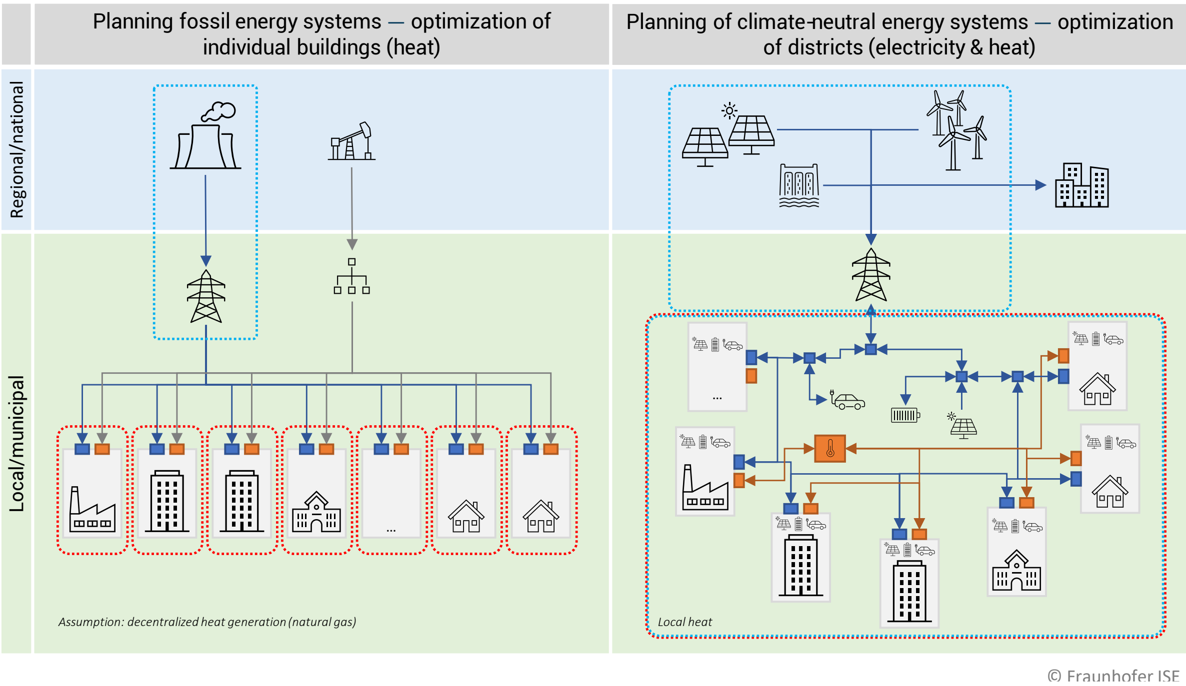


Figure 1 Traditional energy system planning (left-hand diagram): optimization of heat supply at the building level (red dotted line), electricity supply at the regional/national level (blue dotted line); future energy system planning (right-hand diagram): sector-coupled optimization of electricity and heat supply at the local/municipal level (e.g., to districts), simplified illustration. Source: Fraunhofer ISE

The utility of integral energy system planning at the district level is easy to understand as described above. However, this is also associated with additional time, effort and expense resulting from the further development and refinement of planning methods and tools, increased coordination between the energy sectors and between those responsible for energy and urban land use planning, clarification of responsibilities and establishment of processes. Against this background, this study aims to identify the **qualitative and quantitative advantages of a district energy system developed through integrated energy planning over an energy system based on isolated energy planning for individual buildings.**

A comprehensive answer to this question is not possible due to the limited scope of this study. The investigation was therefore limited to the following overall conditions:

- **Consideration of four district types:** Districts differ greatly in terms of size, building density, use (residential, commercial, mixed-use areas), building age (existing buildings of different ages, new construction), and so on. A climate-neutral energy system optimizes location-specific supply options in relation to location-specific demand profiles. This results in a large number of possible combinations. As it would not have been possible to examine all of these possible combinations, four district types with the greatest possible diversity of structures were defined and used as the subject of the subsequent calculations (see section 3.1).
- **Consideration of three fundamental supply structures:** There are three main supply structures for any given district: central supply of both electricity and heat, central supply of electricity but decentralized (building-related) heat supply, and decentralized supply of both electricity and heat. While there is a heating network in the case of a centralized heat supply but not in a decentralized one, there is always an electricity network, but in the third case there is no exchange of electricity between buildings themselves. Many mixed variants are also possible in a district, but to arrive at a broad outline answer to the question, it is sufficient to examine these three supply structures, which are considered below (see section 3.2).
- **Definition of indicators:** It is not easy to evaluate and compare district energy systems in quantitative terms. Once climate neutrality has been achieved, demand for primary energy and CO_2 emissions are no longer sufficient as indicators. On the other hand, the degree of self-sufficiency with locally used renewable energy plays a role, alongside the costs of the energy system.

Considering the mobility sector separately is not viewed as necessary. The researchers assumed that in order to achieve climate neutrality, local transportation within a district would be almost completely converted to electromobility. The electricity needed for local electromobility was taken into account in the electricity load profile (see sections 5.3.3 and 5.4.3). However, long-haul truck, rail and air traffic, which will presumably make significant use of hydrogen and/or e-fuels, was not included in the calculations.

Optimized energy systems have now been calculated for each of the four district types and three supply structures mentioned above for the **target year 2045** using ISE's proprietary KomMod municipal energy system computer model (see section 4). The quantitative advantages of district optimization can be seen by comparing the results of supply variants 1 and 3 (fully centralized versus fully decentralized optimization) and the intermediate step of decentralized heat supply with centralized electricity supply optimization. The results are presented in section 6, and conclusions are drawn in section 8.

3 District types and supply structures

This brief study examined different districts with different energy supply structures. These are presented and characterized below.

3.1 District types

The investigation of the district approach in comparison to an individual building supply was carried out for the target year 2045 using four sample districts, whose characteristics are relevant to the energy system. They consist of different building types and forms of building use. The four sample districts are defined as follows:

- A Refurbishment of an existing urban residential area with medium to high energy demand density (mainly multi-family buildings)
- B Refurbishment of an existing rural residential area with low energy demand density (single-family homes and duplexes)
- C Refurbishment of an urban mixed-use district with medium to high energy demand density and the possibility of waste heat recovery
- D New construction of an urban mixed-use district with medium to high energy demand density and the possibility of waste heat recovery

Each of the districts consists of 40 buildings, with energy requirements varying between districts due to the different building types and forms of use. These 40 buildings are distributed across different building types and types of use, as shown below. The area of each district is not defined. The characteristics of the four districts are shown in table 1.

District A is an urban residential area with apartment buildings. Some of the buildings are older existing buildings having undergone refurbishment by the target year 2045. The MFH_F type building with a construction age between 1969 and 1978 was selected from the IWU typology (Institut Wohnen und Umwelt, 2015) to serve as an example. In addition, the district has experienced partial infill construction and/or some of the older buildings have been demolished and replaced with newer ones. The newer apartment buildings were built between 2010 and 2015 (MFH_K). Furthermore, it is assumed that not all buildings have been refurbished to a level comparable to KfW 40, so the study takes the simplified approach that by 2045 the buildings constructed between 1969 and 1978 have been refurbished to the conventional refurbishment level ("conventional") according to IWU and the buildings constructed between 2010 and 2015 have been refurbished to the future-oriented refurbishment level ("future-oriented"). Section 5.3 takes a closer look at the specific energy requirements that apply to the various levels.

District B is a rural residential area made up of single-family homes and duplexes. As in district A, a mixture of older refurbished buildings and newer buildings constructed in the course of infill and replacement is assumed. The age structure of the buildings is the same as in district A. The older buildings date to the period from 1969 to 1978, while the newer buildings were constructed between

2010 and 2015. The same approach was taken as in district A with regard to the depth of refurbishment, i.e., the older buildings were refurbished to the conventional standard, while the newer buildings were refurbished to the future-oriented standard.

The following tables include the abbreviations “SFH” for single-family home (detached house), “TFH” for two-family home (duplex), “MFH” for multi-family home (apartment housing) and “TCS”, which stands for the trade, commerce and services sector. All further abbreviations can be found in the list of abbreviations at the end of the document.

Category	District A	District B	District C	District D
Location	Urban	Rural	Urban	Urban
Efficiency standard, building types*	Stock refurbished 50% conventional 50% future-oriented	Stock refurbished 50% conventional 50% future-oriented	Stock refurbished 50% conventional 50% future-oriented	New construction 100% future-oriented
District use type	Residential area	Residential area	Mixture: 50% TCS + 50% residential	Mixture: 50% TCS + 50% residential
Number of buildings	40 MFH	40 SFH/TFH	20 MFH + 20 TCS	20 MFH + 20 TCS
Building age	100% postwar	100% postwar	50% prewar + 50% postwar	New construction
IWU building type*	20 MFH_F – k 20 MFH_K – z	20 SFH_F – k 20 SFH_K – z	10 MFH_B – k 10 MFH_K – z 10 TCS retail outlets in MFH_B – k 10 TCS offices in MFH_K – z	20 MFH_L – z 10 TCS retail outlets in MFH_L – z 10 TCS offices in MFH_L – z

* Information refers to the TABULA characterization (Institut Wohnen und Umwelt, 2015). For the TCS buildings, the cubatures of the relevant residential buildings from TABULA are used.

k = conventional refurbishment, z = future-oriented refurbishment

Table 1 Characteristics of the four sample districts

District C is a mixed-use urban district of the kind typically located in city center areas. In 2045, buildings from the period between 1861 and 1918 (MFH_B) will still exist in this quarter. These are considered worthy of preservation, and some of them may also be listed historical properties. Due to infill and the replacement of individual buildings, 50 percent of the buildings are assigned to the MFH_K building type with a construction age of 2010 to 2015. The building density in this district is considered high compared to the other districts. The commercial buildings are divided equally between the office and retail use types. With regard to refurbishment, as in districts A and B, a simplified assumption is made that the older buildings have been upgraded to the conventional refurbishment standard and the buildings of more recent construction age have been refurbished to the future-oriented standard.

District D is a new district that was constructed by the target year and meets the construction standard required in 2045. It is a mixed-use urban district consisting of multi-family residential buildings and commercial buildings. As in district C, half of the commercial use consists of offices and half of retail. All buildings fall within building type MFH_L, which stands for buildings constructed after 2016. Furthermore, it is assumed that all buildings were constructed directly to the KfW 40 standard.

3.2 District energy supply structures

To compare the optimization of an energy system at the district level with optimization at the individual building level only, this study examines the centralized and decentralized supply structures for heat and electricity and also the mixed form in which there is a centralized electricity supply and a decentralized supply of heat. To understand this comparison, it is important to note that in the area of heat, a centralized and decentralized supply is physically determined by the presence or absence of a heating network. In the area of electricity supply, on the other hand, there is always an electricity grid, which in any case permits the exchange of electrons in the grid. The distinction between centralized and decentralized optimization in the electricity sector is therefore made not at the physical level, but rather at the economic and regulatory level, for example in that the solar power generated on the roof of one building may or may not also be consumed by a neighboring building.

The following three supply variants are compared:

1. **Central heat supply and central electricity optimization:** Heat is supplied to all buildings via a heating network that can have different flow temperatures and heat sources (biomass CHP, geothermal energy, solar thermal energy, waste heat, heat pumps). The electricity supply is optimized for the district, with the result that electricity can be exchanged between all buildings.
2. **Decentralized heat supply and central electricity optimization:** Each building has its own independent form of heat generation (solutions depend on the building types and sizes). The power supply is optimized for the district, allowing electricity to be exchanged between all buildings.
3. **Decentralized heat supply and decentralized electricity optimization:** The heat supply and electricity supply are optimized separately for each building; there is no exchange of heat or electricity between the buildings.

The different characteristics of the three supply structures result in different possible energy sources and supply technologies, some of which also differ for the four district types in table 2. These are described below.

Supply structure 1: In the first supply variant, all buildings in all districts are connected to a heating network and are supplied with heat centrally. Large heat pumps and solar thermal energy are available for this purpose in all districts. In districts A, B and C, CHP units can also be used to generate electricity as well as heat. In districts A and C, which are both urban, the CHP units are fed with biogas imported from the surrounding area, while the use of wood pellets is assumed for the rural district B. Wood pellet boilers are also available in this district to cover peak loads. In districts C and D, it is also assumed that waste heat from a nearby industrial plant can be used as a heat source in the district. The waste heat is provided at 40°C and can cover a maximum of 50 percent of the heat demand and 50 percent of the maximum load of the heat demand for this network. In all districts except D, heat is supplied via the heating network at a temperature of 70°C all year round. There are two reasons for this: First, the domestic hot water supply is also to be provided via the heating network, and second, it is assumed that not all old buildings could be converted to low-temperature space heating and some still require heat at a temperature level of 70°C. Therefore, the temperature of the waste heat still has to be raised from 40°C to 70°C via a heat pump at the district's heating center. District D is the exception here. As all the buildings here meet the KfW 40 standard for new construction, demand for space heating can be met at a temperature level of 40°C, so there is no need to raise the temperature of the waste heat. However, the temperature of the domestic hot water does still have to be raised from 40°C to 70°C on a decentralized basis, using booster heat pumps in the buildings. The same proportion of energy grid losses is assigned to the heating networks across all districts, as a granular consideration of differences in heating networks is not the focus of this brief study.

In variant 1, demand for electricity in the buildings can be covered on the one hand by solar panels on the buildings and on the other by electricity from the CHP unit. Regional wind power can also be used. It is assumed that a power purchase agreement (PPA) will be concluded with the wind turbine operators, resulting in an additional 5 cents/kWh in remuneration or grid charges for the district over and above the electricity generation costs for the wind energy. Electricity imports can also help to cover the demand for electricity. Solar and CHP electricity can be used anywhere in the district without further restrictions, and there are no grid fees and/or charges for use. The legal situation of this supply variant is discussed in section 7.

Supply variant 2: In the second supply variant, the electricity supply is optimized for the district as in variant 1, while the heat supply is decentralized, and no heating network is installed in the district. Solar thermal systems can be used to supply heat to the individual buildings in all districts, and heat pumps supplied with environmental heat either via a geothermal probe or via the outside air are available in all districts except district C. For this district, it is assumed that heat pumps cannot be used on a decentralized basis for various reasons (e.g., space constraints due to the densely constructed city center setting, noise emissions, flow temperatures of the heating systems, caveats, etc.). Instead, the use of micro-CHP systems paired with heating rods is possible to cover peak loads here. In district B, wood boilers represent another option, as it is assumed that biomass is more readily available in rural areas than in the city. The temperature levels of the heat supply are the same as in supply variant 1.

Supply variant 3: The third supply variant corresponds to variant 2 in terms of heat supply, but there is no district-optimized electricity supply in the sense of volumes of electricity being exchanged between buildings. Instead, the electricity supply is optimized for individual buildings. This means that each building can install solar panels for its own electricity needs and use that power itself, but the surplus cannot be used in the other buildings in the district, but must instead be fed into the power grid. There are also no plans to use regional wind power, as it is not assumed that the owners of individual buildings will sign PPAs with the wind farm operators. Importing electricity from the public grid is still possible for every building.

Energy supply, district type			Variant 1	Variant 2	Variant 3
			Heat centralized Electricity centralized	Heat decentralized Electricity centralized	Heat decentralized Electricity decentralized
A	Urban housing stock	Heat	Large-scale HP (geothermal probe), ST, biogas CHPG Grid FT 70°C	Small HP (geothermal probe, air), ST	Small HP (geothermal probe, air), ST
		Elec.	PV local, biogas CHP local, wind regional, electricity import	PV local, wind regional, electricity import	PV local, electricity import
B	Rural housing stock	Heat	Large-scale HP (geothermal probe), ST, wood CHPG, peak load wood boiler Grid FT 70°C	Small HP (geothermal probe, air), ST, wood boiler	Small HP (geothermal probe, air), ST, wood boiler
		Elec.	PV local, wood CHPG local, wind regional, electricity import	PV local, wind regional, electricity import	PV local, electricity import
C	Urban stock mix	Heat	Waste heat 40°C (incl. waste), large-scale HP (geothermal probe, waste heat increased from 40°C to 70°C), ST, biogas CHPG, heating rods Grid FT 70°C	Biogas micro-CHPG, ST, heating rods	Biogas micro-CHPG, ST, heating rods
		Elec.	PV local, biogas CHPG local, wind regional, electricity import	PV local, wind regional, electricity import	PV local, electricity import
D	Urban new constructio n mix	Heat	Waste heat 40°C (incl. waste), large-scale HP (geothermal probe, increased to 40°C), booster HP (increased from 40°C to 70°C), ST Grid FT 40°C, DHW temperature increased to 70°C on a decentralized basis	Small HP (geothermal probe, air), ST	Small HP (geothermal probe, air), ST
		Elec.	PV local, wind regional, electricity import	PV local, wind regional, electricity import	PV local, electricity import

HP = heat pump, PV = photovoltaics, ST = solar thermal, CHPG = combined heat and power generation, FT = flow temperature, DHW = domestic hot water

Table 2 Overview of the possible energy sources and supply technologies for the three energy supply variants and the four district types

4 Energy system modeling with KomMod

The KomMod municipal energy system model serves as a computer model for calculating optimized target energy systems for municipalities and districts. To this end, it maps the energy system, including the demand sectors of electricity, heating, cooling and transport, for a given district, municipality, region or property for any target year as a system of mathematical equations. The program simultaneously optimizes the structure and operation of the energy supply system according to the target values of minimum total costs, minimum emissions or maximum energy autonomy. To this end, the energy demand expected in the target year is specified, along with the available potential for renewable energy and the availability of other energy sources. The possible supply technologies and their technical and economic parameters are used as further input data, as KomMod is designed as a techno-economic bottom-up model.

The model's methodological core consists of mapping and simultaneously taking into account as many interactions as possible between the individual components within the energy system for each time unit under consideration. This concerns, for example, the interactions between the electricity and heat sectors through combined heat and power generation or electric heat pumps. The calculations are carried out with high temporal resolution in order to adequately take into account the dynamics of the energy system. The optimization calculations for the target year are usually carried out in hourly resolution, i.e., the energy calculations are optimized simultaneously for 8,760 hours. Figure 2 shows a generic diagram of the district energy system with all energy links that are mapped in KomMod. The available components and their specific properties are taken into account in the modeling.

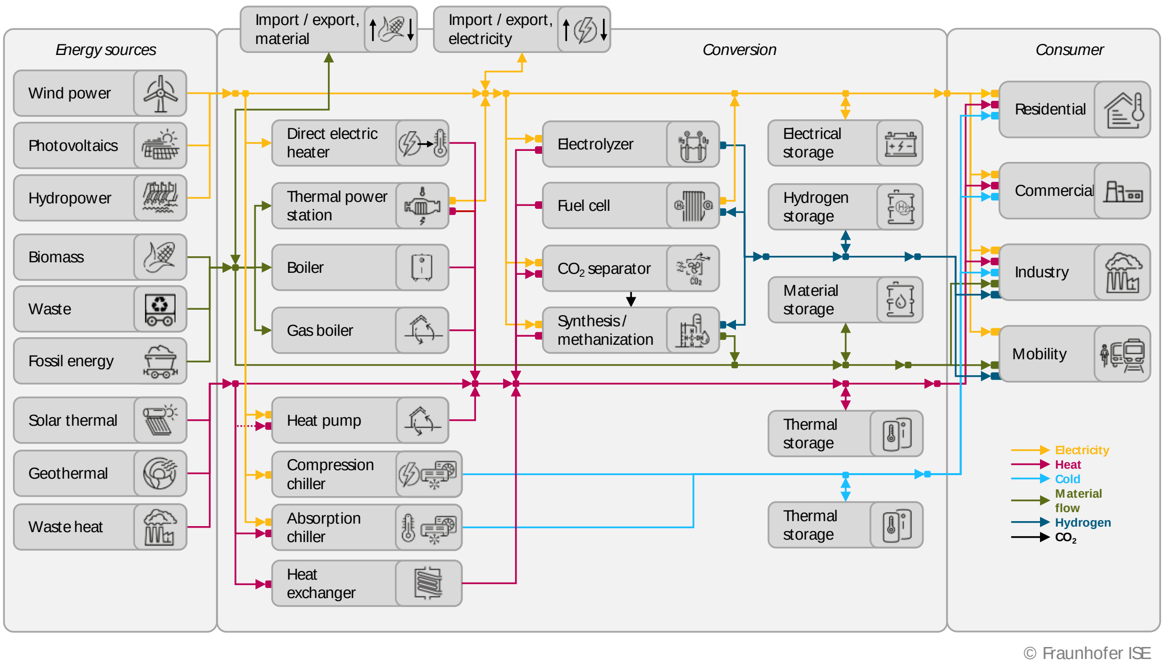


Figure 2 Generic diagram of the energy system of a climate-neutral district with all possible energy flows between the components as the basis for KomMod modeling. Source: Fraunhofer ISE

As the result of the optimization calculations, KomMod provides an energy system design with the requisite installed capacities of generation and conversion plants as well as storage systems. Furthermore, the operating mode of the energy system is optimized, along with — to that end — the maximum occurring energy flows and the annual energy quantities that are generated, converted or stored per component. Further results are full load hours per plant, partial plant locations and land requirements as well as costs and carbon dioxide emissions for each plant type and for the overall system. Imports and exports of various energy sources are also recorded in terms of output and energy quantities. Time series can be outputted for all energy flows.

A parameter set that summarizes the input data as boundary conditions for the modeling defines what is known as a scenario. In order to investigate different aspects of the energy system or the effects of changed boundary conditions, the input data are varied in a targeted manner, which causes several scenarios to be configured and calculation runs carried out. Comparing the calculation results makes sensitivity analyses possible.

5 Input data and boundary conditions of the scenarios

This section presents all the input data for the short study and the methods used to calculate and generate individual data.

5.1 Demographics, building occupancy and district composition

One important basis for the studies is the population level assumed for the target year, 2045, and the building occupancy of the building types under consideration (see section 3.1), which are key factors in determining energy demand within the districts. The German Federal Statistical Office's "BEV-VARIANTE-02" scenario (Statistisches Bundesamt (Destatis), 2021) is used for the population of Germany in 2045, which in turn is used to calculate demand for electromobility (see section 5.3.3).

To calculate the building occupancies of the building types examined in the target year, it is assumed that they correspond to the current occupancies. Data from (Institut Wohnen und Umwelt, 2015) and (Statistisches Bundesamt (Destatis), 2011) are used and offset against each other to calculate the current building occupancy of the buildings examined. Thus, an average number of apartments per building is identified as the first step, and the number of people per building is determined next. No distinction is made here on the basis of the refurbishment status of the buildings examined, but a distinction is made between single-family homes (SFH) and multi-family houses (MFH).Table 3 shows the information on the building occupancy of the building types examined. Since the districts examined in the study do not represent real districts, but rather are intended to serve as references, odd numbers of apartments per building, persons per apartment or persons per building are not rounded.

Building type	Number of buildings in Germany	Number of apartments in Germany	Average number of apartments per building	Average number of persons per apartment	Persons per building
SFH_F	1,507,000 [I]	1,915,000 [I]	1.27	2.52 [IV]	3.20
SFH_K	1,498,098 [II]	1,498,098 [II]	1.00	2.52 [IV]	2.52
MFH_B	442,000 [I]	2,177,000 [I]	4.93	1.71 [V]	8.42
MFH_F	412,000 [I]	2,313,000 [I]	5.61	1.71 [V]	9.60
MFH_K	157,862 [III]	856,009 [III]	5.42	1.71 [V]	9.27
MFH_L	157,862 [III]	856,009 [III]	5.42	1.71 [V]	9.27

[I] Source: (Institut Wohnen und Umwelt, 2015) for 2009; [II] calculated from (Statistisches Bundesamt, 2011) from difference between December 31, 2020, and December 31, 2009, for residential buildings with 1 housing unit; [III] calculated from (Statistisches Bundesamt, 2011) from difference between December 31, 2020, and December 31, 2009, for residential buildings with at least 3 housing units; [IV] calculated from (Statistisches Bundesamt, 2011) for buildings with 1 housing unit; [V] calculated from (Statistisches Bundesamt, 2011) for buildings with 3 to 6 housing units.

Table 3 Building occupancy of the different building types

Table 4 provides an overview of the number of buildings in the district, the energy reference areas, the roof areas and the residents per building type. It is clear that the different types of residential building offer different amounts of living space per person, which results from the calculated and assumed building occupancy shown in table 3.

Dis-trict	Building type	Energy reference area per building according to (Institut Wohnen und Umwelt, 2015) (m²)	Energy reference area in the district (m²)	Roof area per building according to (Institut Wohnen und Umwelt, 2015) (m²)	Roof area in the district (m²)	Number of residents per building
A	MFH_F	426.01	32,000.20	216.70	10,755.00	9.60
	MFH_K	1,219.00		321.05		9.27
B	SFH_F	157.50	6,358.00	183.13	6,300.60	3.20
	SFH_K	160.40		131.90		2.52
C	MFH_B	284.00	30,060.00	102.80	8,477.00	8.42
	MFH_K	1,219.00		321.05		9.27
	TCS retail outlets in MFH_B	284.00		102.80		–
	TCS offices in MFH_K	1,219.00		321.05		–
D	MFH_L	1,219.00	48,760.00	321.05	12,842.00	9.27
	TCS retail outlets in MFH_L	1,219.00		321.05		–
	TCS offices in MFH_L	1,219.00		321.05		–

Table 4 Overview of the buildings in the four districts with energy reference areas, roof areas and number of residents

5.2 Climate data

To ensure the comparability of the results, all calculations are carried out for Potsdam as a location. The climate data for Potsdam as a location was obtained from the German Weather Service (DWD), with the Test Reference Year (TRY) used constituting synthetic climate data (German Federal Office for Building and Regional Planning (BBR), German Weather Service (DWD), 2017), which are provided in a grid of 1 x 1 km² for the whole of Germany. In addition to data reflecting the current climate, future climate data are also available for use for the period from 2031 to 2060. These include the projected effects of climate change. As this study is concerned with calculating scenarios for the year 2045, the TRY data for 2031–2060 are used. The 1 x 1 km² tile with coordinates 52.3651°N and 13.0936°E (World Geodetic System, 1984) is selected as the reference point. The mean annual temperature is 10.95°C with a fluctuation of -8.3°C to +31.9°C. The annual solar radiation on a horizontal surface is 1,071 kWh/(m²•a), and the average wind speed at a height of 10 m is 3.3 m/s.

5.3 Annual energy requirements

This section describes the methods used to determine the annual energy requirements of all types of buildings for electricity, space heating and hot water.

5.3.1 Electricity demand, households

Annual electricity requirements in households are most strongly correlated with the number of occupants of the units in a building, which is why the annual electricity requirements of each building type are determined using this parameter. As shown in section 5.1, data from (Statistisches Bundesamt, 2011) is used to determine the average number of people living in a household. The calculation is carried out separately for single/two-family houses and multi-family houses (SFH, TFH, MFH). The TABULA data from the IWU (Institut Wohnen und Umwelt, 2015) are used to determine the average number of apartments in each type of building. (co2online gemeinnützige GmbH, 2019) shows how much electricity was consumed in households in Germany in 2019, depending on the number of residents. This present-day electricity consumption is used as a guide to determine the electricity requirements in the target year. In order to take account of efficiency gains, but at the same time factor in rising electricity demand resulting from increased comfort and new consumers of electricity, values from the more-efficient classes of the Stromspiegel (co2online gemeinnützige GmbH, 2019) are used for the target year, 2045. This results in annual electricity demand of 2,758 kWh/a per unit for the single-family homes under consideration and 1,426 kWh/a per apartment for multi-family homes. The electricity consumption per apartment and the number of apartments per building can then be used to calculate the electricity consumption per type of building. The input data and the calculated electricity requirements are shown in table 5. The specific electricity demand of the building types can be determined using the energy reference areas specified in TABULA (Institut Wohnen und Umwelt, 2015). This yields a mixed picture due to the different amounts of living space per person in the various building types.

Building type	Housing units per building	Persons per building	Electricity demand per unit (kWh/a)	Electricity demand per building (kWh/a)	Specific electricity demand (kWh/(m²•a))
SFH_F	1.27	3.20	2,758	3,504	22.25
SFH_K	1.00	2.52	2,758	2,758	17.19
MFH_B	4.93	8.42	1,426	7,023	24.73
MFH_F	5.61	9.60	1,426	8,005	18.79
MFH_K	5.42	9.27	1,426	7,732	6.34
MFH_L	5.42	9.27	1,426	7,732	6.34

Table 5 Calculation of the electricity demand per building for all building types with residential use from the scenarios

5.3.2 Electricity demand from trade, commerce and services

Energy consumption can vary greatly for companies in the trade, commerce and services (TCS) sector. As a basis for this study, specific electricity consumption for buildings with office use and for retail outlets was evaluated from two studies. The electricity consumption determined and the (average) values used in this study are shown in table 6. This table makes it clear that the types of commercial buildings used have significantly higher specific electricity requirements than the residential buildings (see tables 5 and 6).

Industry	Specific electricity consumption from (IB Cornelsen Hamburg, 2021) (kWh/(m²•a))	Specific electricity consumption from (Bayer et al., 2011) (kWh/(m²-a))	Specific electricity consumption averaged, today (kWh/(m²•a))
Offices	55	60–150	88
Sales outlets/retail, non-food and food	270	–	270

Table 6 Calculation of the electricity demand per building for all type buildings with residential use from the scenarios

The cubatures of residential buildings from the TABULA typology (Institut Wohnen und Umwelt, 2015) are used to illustrate the cubatures of TCS buildings, and the types of residential buildings used are also indicated below. It can be presumed that specific electricity consumption will decrease between now and 2045. Total electricity consumption in the TCS sector is forecast to decrease by 25.5%

between 2020 and 2045. In the absence of data to the contrary, this was assumed for all types (Deutsche Energie Agentur GmbH (dena), 2021a, 2021b). The specific electricity consumption is multiplied by the energy reference area of the type buildings (from TABULA (Institut Wohnen und Umwelt, 2015)) in order to calculate the absolute annual electricity consumption. The calculated annual electricity consumption of the TCS type buildings for the year 2045 is shown in table 7.

	Specific electricity demand, 2045 (kWh/(m²•a))	Reference area (m²)	Electricity demand per building, 2045 (MWh/a)
TCS retail outlets in MFH_B – k *	201.09	284	57.11
TCS offices in MFH_K – z *	65.54	1,219	79.89
TCS retail outlets in MFH_L – z *	201.09	1,219	245.12
TCS offices in MFH_L – z *	65.54	1,219	79.89

* Cubature based on the relevant residential buildings in (Institut Wohnen und Umwelt, 2015)
k = conventional refurbishment, z = future-oriented refurbishment

Table 7 Specific and absolute electricity consumption of TCS-type buildings in 2045

5.3.3 Electromobility

Calculating the energy demand for mobility in the target year, 2045, is rife with uncertainty, as it depends on the types of mobility, the engine types considered, the mobility behavior assumed, the number of vehicles and the energy consumption as a function of distance traveled. It is only possible to make assumptions for all of these factors, without certainty. Only the private and commercially used cars in the district are taken into account, and it is assumed that 100 percent of these are electric vehicles (EVs), with the result that the power needed to charge these vehicles is attributed to the district. It is assumed that the annual mileage in the target year is equivalent to the current values of 12,300 km/(car•a) in private use and 24,500 km/(car•a) in commercial use (German Federal Highway Research Institute, 2017). According to the Ariadne study, the total number of cars (for passenger and commercial transportation) in Germany is expected to stand at 36,010,000 in 2045 (Luderer et al., 2021). This figure is then used together with the forecast German population of 81,580,000 in 2045 according to the "BEV-VARIANTE-02" scenario (Federal Statistical Office (Destatis), 2021), which matches the assumptions of the Ariadne study, to calculate the number of cars per capita, which ends up around 0.44 cars/inhabitant. The number of inhabitants per district (see section 5.1), number of cars per inhabitant and annual mileage per car are used to calculate the annual mileage of private trips per district. For the TCS sector, a simplified assumption is made that the number of commercially used vehicles per building corresponds to that of a residential building of the same assumed cubature. This assumption is used to calculate the number of commercially used cars per district, and the annual mileage per car is used to calculate the annual mileage per district in the TCS sector. Average electricity consumption of 15 kWh/100 km is assumed in order to calculate the annual electricity requirements for mobility based on the total annual mileage of the respective districts. Table 8 shows the key input data on the energy requirements for the mobility of the districts as considered in the study.

District	Building type	Annual mileage per building type in the district (1,000 km/a)	Electricity demand for cars per building type in the district (MWh/a)	Electricity demand for electromobility in the district (MWh/a])
A	MFH_F	1,042.37	156.36	307.38
	MFH_K	1,006.81	151.02	
B	SFH_F	347.10	52.07	93.04
	SFH_K	273.15	40.97	
C	MFH_B	457.25	68.59	431.12
	MFH_K	503.40	75.51	
	TCS retail outlets in MFH_B	910.78	136.62	
	TCS offices in MFH_K	1,002.71	150.41	
D	MFH_L	1,006.81	151.02	451.83
	TCS retail outlets in MFH_L	1,002.71	150.41	
	TCS offices in MFH_L	1,002.71	150.41	

Table 8 Key parameters for districts' mobility-related demand for energy in the target year

5.3.4 Heating requirements, residential buildings

The specific heating consumption for residential buildings can be taken from the IWU typology for the relevant defined refurbishment status (see also section 3.1), and the reference areas for the heating consumption are also known for each type of building (Institut Wohnen und Umwelt, 2015).

The IWU typology provides both the heating demand, i.e., the calculated value, and the consumption value of the buildings measured. An evaluation by the IWU showed that the calculated requirements for old, poorly insulated buildings usually exceed consumption, while the opposite is true of new, well-insulated buildings. This study uses actual consumption values (except in the case of MFH_L) in order to depict conditions that are as realistic as possible. Present-day specific heating consumption is shown in Table 9.

Table 10 shows the heating requirements for the target year, 2045, broken down into conventional (k) and future-oriented (z) refurbishment levels. It is assumed that the older building types in the existing districts will have been refurbished to the conventional refurbishment level by the target year. The newer building types in the existing districts have been refurbished to the future-oriented refurbishment level, and the new buildings in district D were also built to this standard. The future-oriented refurbishment and new construction correspond to KfW 40. The heating requirements associated with conventional refurbishment stand at 61.2 to 64.8 percent of the present-day heating requirements, while the heating requirements associated with future-oriented refurbishment are between 21.3 and 27 percent of that figure.

Consumption today	District A (kWh/(m²•a))	District B (kWh/(m²•a))	District C (kWh/(m²•a))	District D (kWh/(m²•a))
SFH_F — today		153.41		
SFH_K — today		94.28		
MFH_B — today			144.61	
MFH_F — today	131.34			
MFH_K — today	77.50		77.50	
MFH_L — today				77.50

Table 9 Current specific heating consumption of all types of buildings with residential use according to (Institut Wohnen und Umwelt, 2015)

Requirements, 2045	District A (kWh/(m²•a))	District B (kWh/(m²•a))	District C (kWh/(m²•a))	District D (kWh/(m²•a))
SFH_F – k		99.39		
SFH_K – z		25.52		
MFH_B – k			88.55	
MFH_F – k	81.36			
MFH_K – z	16.48		16.48	
MFH_L – z				16.48

Table 10 Specific heating requirements of all types of buildings with residential use for the year 2045 in the conventional (k) and future-oriented (z) refurbishment variants used according to (Institut Wohnen und Umwelt, 2015)Click or tap here to enter text.

5.3.5 Heating requirements for domestic hot water, residential buildings

Like the specific demand for heating, the specific heat requirements for domestic hot water heating can be taken from the IWU typology for each type of building with residential use at each refurbishment level. The current requirements for the types of buildings are listed in table 11. The values for the energy requirements for domestic hot water heating in 2045 are shown in table 12.

Consumption today	District A (kWh/(m²•a))	District B (kWh/(m²•a))	District C (kWh/(m²•a))	District D (kWh/(m²•a))
SFH_F – today		7.55		
SFH_K – today		11.65		
MFH_B – today			12.13	
MFH_F – today	12.85			
MFH_K – today	16.06		16.06	
MFH_L – today				16.06

Table 11 Current domestic hot water consumption per m² of living space according to (Institut Wohnen und Umwelt, 2015)

Requirements, 2045	District A (kWh/(m²•a))	District B (kWh/(m²•a))	District C (kWh/(m²•a))	District D (kWh/(m²•a))
SFH_F – k		10.43		
SFH_K – z		11.65		
MFH_B – k			16.05	
MFH_F – k	16.26			
MFH_K – z	16.06		16.06	
MFH_L – z				16.06

Table 12 Domestic hot water requirements per m² of living space forecast for 2045 based on (Institut Wohnen und Umwelt, 2015)Click or tap here to enter text.

5.3.6 Heat demand in trade, commerce and services

Three studies were evaluated to estimate the specific heating requirements for the two TCS types, office and retail premises, and an average value was calculated. The values are shown in table 13.

The future consumption values in 2045 were calculated on the assumption that the expected 30.5 percent reduction in heating demand for the TCS sector as a whole between 2020 and 2045 also applies to the two TCS sector types (Deutsche Energie Agentur GmbH (dena), 2021a, 2021b). This reduction in demand results in the specific heating requirements of the TCS types estimated for 2045 (see table 13). To simplify matters, this brief study assumes that these specific heating requirements are the same for all TCS buildings of the same type and that no distinction is made according to the buildings' age class. This means that both existing buildings and new buildings of the same TCS type have the same specific heating requirements.

Specific heat consumption and requirements	According to (Henger et al., 2016) (kWh/(m²•a))	According to (IB Cornelsen Hamburg, 2021) (kWh/(m²•a))	According to (Bayer et al., 2011) (kWh/(m²•a))	Values used in this study for today (kWh/(m²-•a))	Requirements for 2045 (kWh/(m²•a))
Offices	132.6	135.0	150–190	151.90	104.32
Sales outlets/retail, non-food and food		150.0		150.00	105.64

Table 13 Current specific heat consumption and future (2045) heat demand per m² of floor space for the TCS types of office and retail space

5.3.7 Heating networks and network losses

Energy supply variant 1 in this study (see section 3.2) is characterized by the central provision of heat by means of a heating network. General assumptions were made regarding the energy and techno-economic properties of the heating networks. It was not possible to consider specific parameters such as nominal pipe diameters, route meters, etc. within the scope of the study, and this would not have been expedient in any case with regard to the general question explored here. In part for reasons of comparability, it was assumed that the heating networks in all districts have the same characteristics and the same pipe length of 57 meters on average per building connection (Pfnür et al., 2016). Furthermore, the same average network losses of 13 percent were assumed, equivalent to the current average for Germany as a whole (Pfnür et al., 2016). This increases the heat demand of the districts in supply variant 1 accordingly. In addition, the costs of the heating networks are the same in all four districts (see section 5.6).

5.4 Load profiles of the energy requirements

Load profiles are required for all energy types in hourly resolution over an entire year (8,760 hours) for the target year in order to carry out the modeling. The annual demand values do not differ between variant 1 (district view), variant 2 (mixed view) and variant 3 (individual building view). The load profiles, on the other hand, differ across the variants, as demand for energy in different households and buildings does not arise at exactly the same time, so the demand profile is smoothed in the district analysis. For this reason, different load profiles were used for almost all energy types and aggregation levels, depending on whether the overall district supply or the individual building supply is examined in the respective scenario. The choice of load profiles is important for the results of the study, as solar panels and wind energy are two fluctuating renewable sources of energy (see section 3.2) and how the load profiles are defined has a direct influence on the simultaneity of fluctuating renewable electricity generation and energy demand.

5.4.1 Electricity load profile, district

In the supply variants in which electricity can be exchanged between all buildings (variants 1 and 2), the standard load profiles of the German Association of Energy and Water Industries (BDEW) were used for household customers and for various types in the TCS sector (Meier et al., 1999; Bundesverband der Energie- und Wasserwirtschaft e. V. (BDEW), 2017). The standard load profile for electricity represents the typical demand for electricity, differentiated by season and day of the week, in 15-minute increments. However, it only applies starting at a certain number of households and buildings, as it was developed to enable electricity suppliers to forecast electricity demand in their supply areas. There are 40 buildings in all districts, a number of households deemed sufficient for the use of standard load profiles. District B has the fewest households, as it consists exclusively of single-family homes and duplexes, or two-family houses. There are a total of around 45 housing units in district B. This is considered sufficient to use the standard load profile.

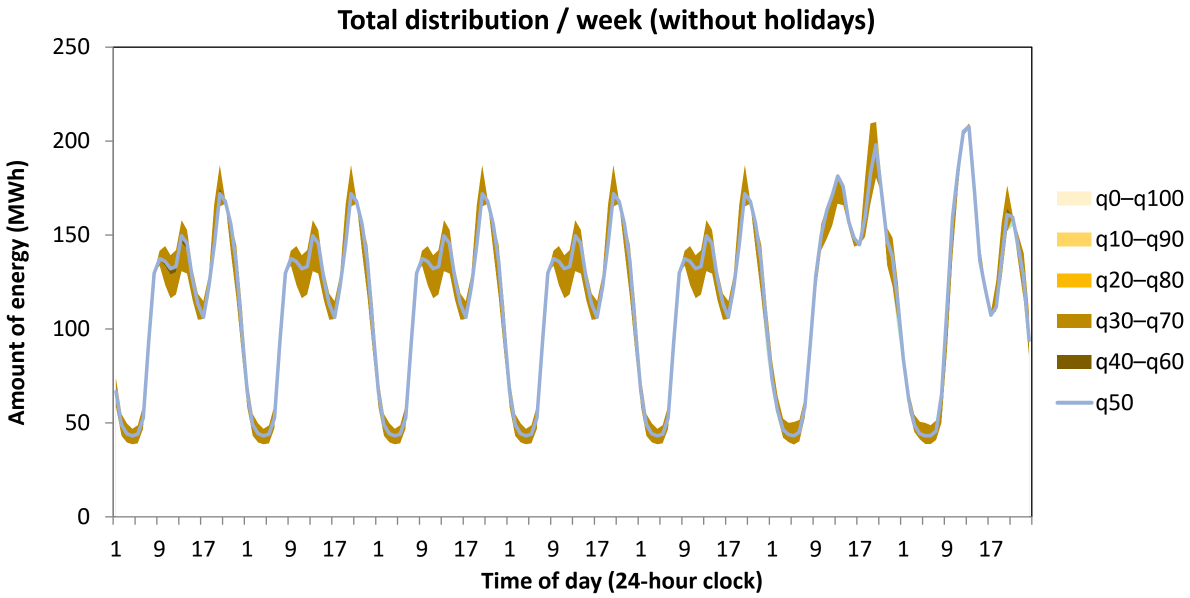


Figure 3 Standard one-week electricity load profile for households in 15-minute resolution[1]

The standard electricity load profile for households (H0) shown in figure 3 was used for the entire district (variants 1 and 2). A week without holidays is shown, with the median and different quantiles over the one-year observation period. The office buildings use the G1 profile (see figure 4), while retail outlets use G4 (see figure 5), which are shown in the figures with their overall distribution over

[1] q refers to the respective quantiles of the distribution. They describe interval limits for the values of the total quantity sorted in ascending order. q0-q100 covers the total quantity of all weekly values, and q0-q10 would, for example, describe the interval of the lowest 10 percent of all values. The interval q40-q60 comprises 20 percent of the total quantity of all values. q50 denotes the median. The figure shows that the values fluctuate only slightly around the median over the course of the week.

one day for the one-year observation period. Individual load profiles were used for the individual buildings (see section 5.4.2).

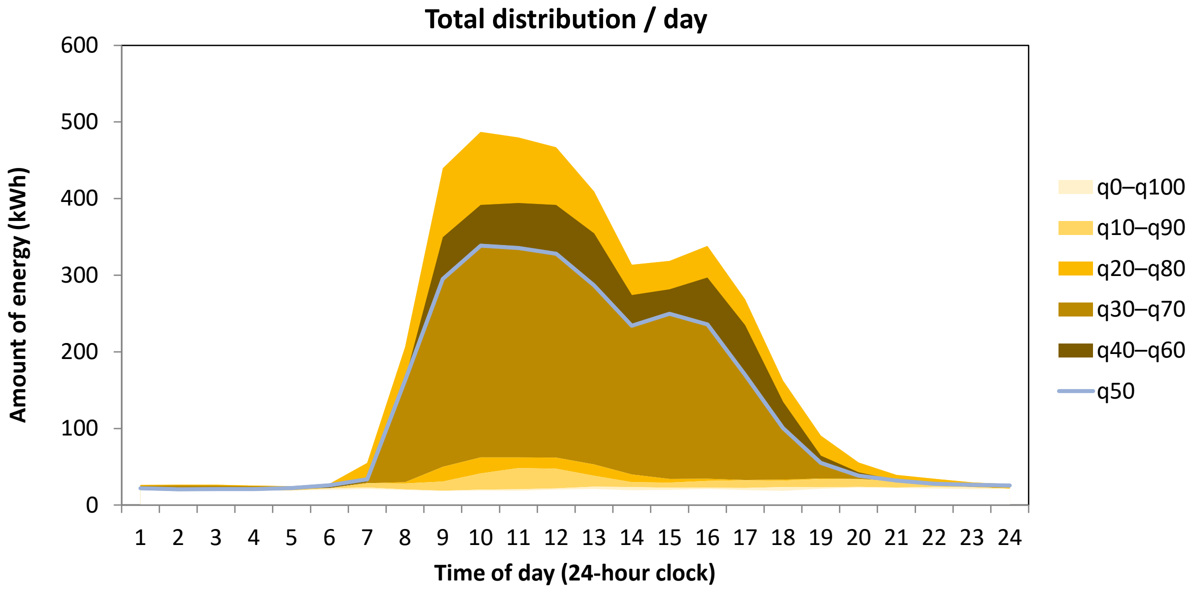


Figure 4 Standard load profile for office buildings in hourly resolution

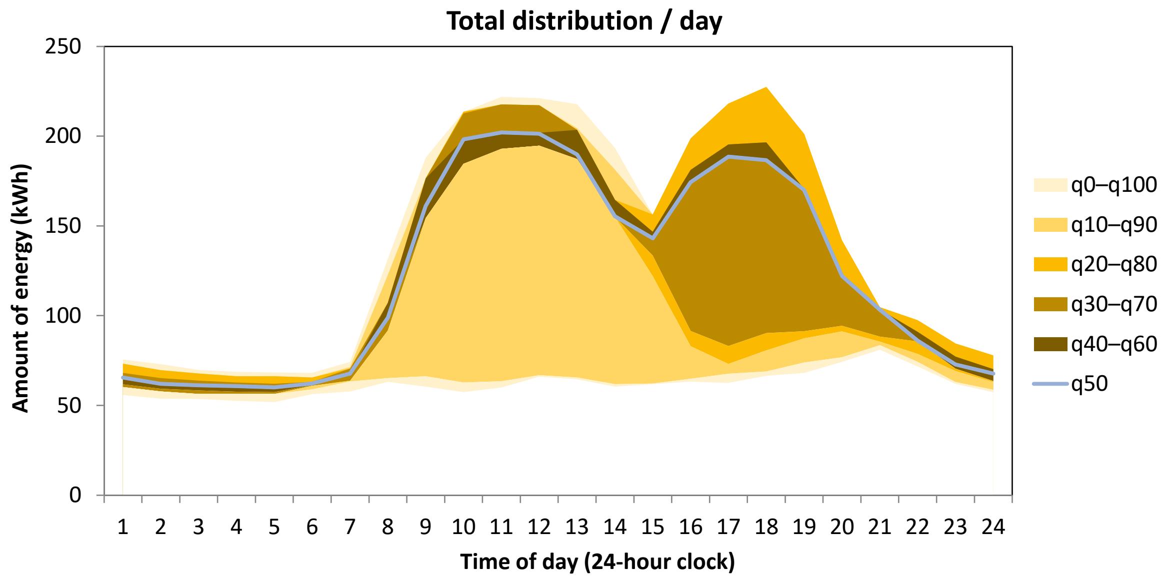


Figure 5 Standard load profile for retail outlets in hourly resolution

5.4.2 Electricity load profile, individual buildings

When it comes to investigating variant 3, in which the individual buildings are considered separately, standard load profiles cannot adequately reflect the dynamics of electricity demand. Therefore, real-world household load profiles from (Beyertt et al., 2020) are used for the electricity load profiles of the residential buildings. The data set associated with this publication contains 200 load profiles for real households in Germany as measured via smart meters in the period from January 1, 2019, to

January 31, 2020. The households received a monthly electricity report as part of the project and were able to adjust their behavior accordingly. For the sake of simplicity, it is assumed that these real-world profiles reflect the electricity load profiles of households in the target year. The load profiles from this data set are used for the 2019 period, converted into hourly profiles and standardized. From these 200 profiles, different profiles are randomly assigned to the buildings under investigation based on the rounded number of housing units per building (see table 5). The resulting overall profiles per building are scaled using the annual electricity demand for the respective building. Figure 6 shows the aggregated electricity load profile for residential buildings of the MFH_F type with a statistical distribution over one day around the median (q50).

Due to the poor availability of data and inability to generalize from the measured load profiles of individual buildings in the TCS sector, the standard load profiles of the TCS buildings used for the overall districts are also used for the individual buildings and scaled using their respective annual electricity requirements. As previously, the G4 standard load profile from (Meier et al., 1999; Bundesverband der Energie- und Wasserwirtschaft e. V. (BDEW), 2017) is assigned to the TCS buildings of the type "retail outlet," and the G1 standard load profile from the same publication is assigned to those of the type "office."

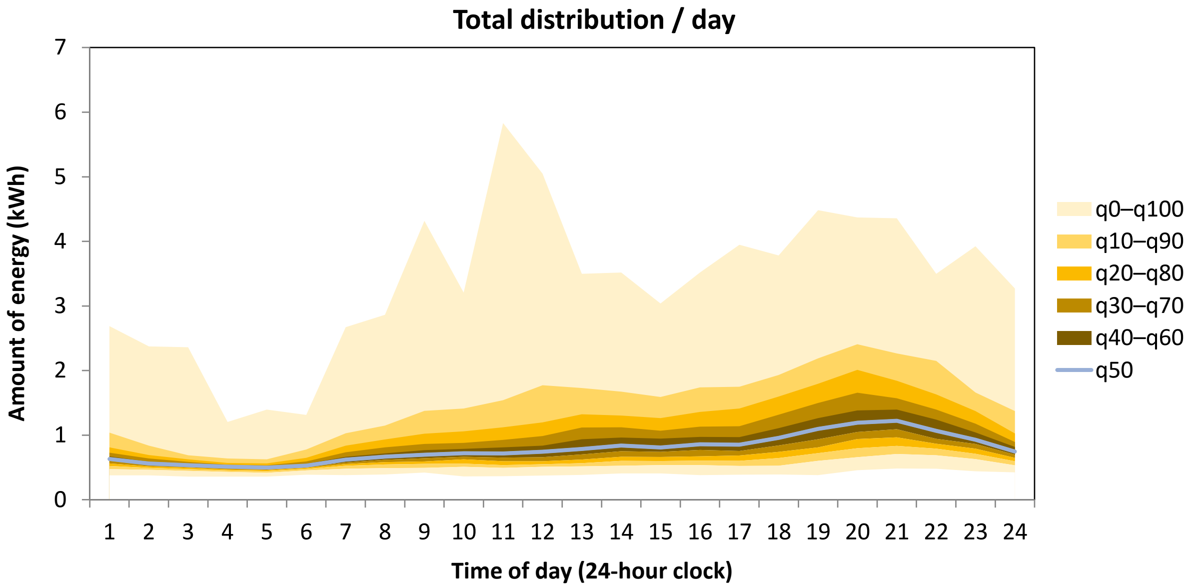


Figure 6 Aggregated electricity load profile for individual residential buildings of type MFH_F

5.4.3 Electricity load profiles, electromobility

The characteristics of the electricity load profiles of electric vehicles (EVs) in the target year are also determined as an input variable for modeling purposes. Controlled and bidirectional charging is assumed to be the prevailing method in the target year. The availability of EV battery capacity is implicitly mapped within the modeling as storage capacity by means of bidirectional charging via mapping as stationary battery storage, leading to identification of the residual profile of the electromobility charging process. To map the controlled charging curves, two approaches for charging profiles of electric vehicles are combined with equal weighting, and the result is shown for the EVs assigned to an MFH_F in figure 7 for the statistical distribution of a year over one day. This load profile for charging EVs is added to the buildings' electricity load profile.

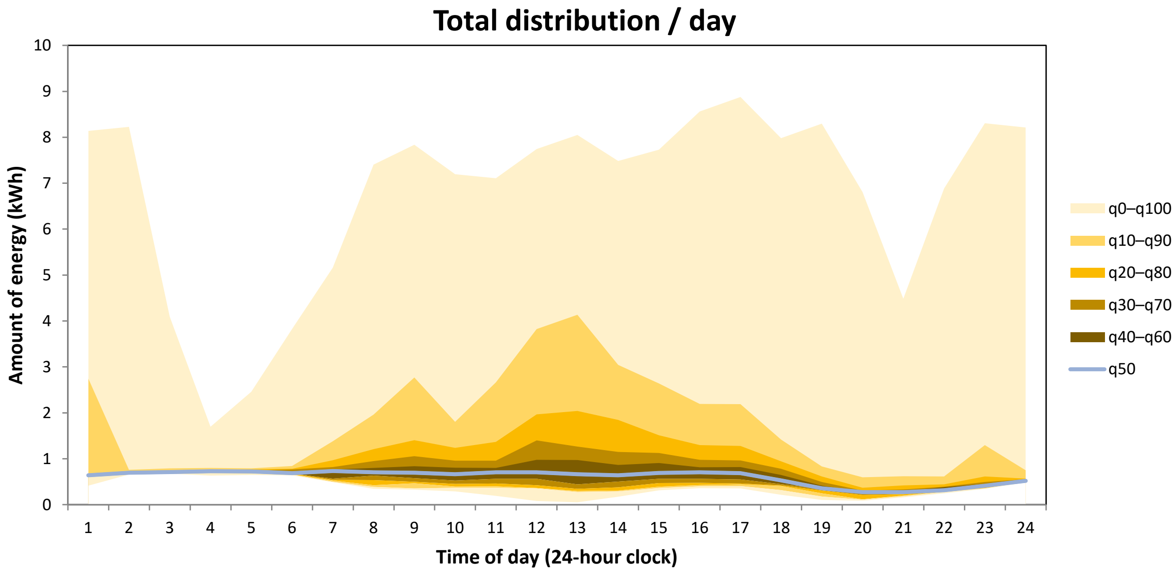


Figure 7 Charging profile of all electric vehicles assigned to a residential building of type MFH_F

The first method pursues optimization of self-consumption from solar panels at the district level for districts that have a significant proportion of photovoltaic electricity generation. The optimization algorithm and the profiles were developed based on (Sprengeler et al., 2019) within (Lambert, 2020) and use real data from the EnStadt:Pfaff project (Federal Ministry for Economic Affairs and Energy (BMWi) and Federal Ministry of Education and Research (BMBF), 2021).

The second method is based on the electricity demand profiles of the relevant district. It presents the controlled charging in such a way that additional load peaks are prevented as far as possible and controlled charging of EVs takes place at times of low electricity consumption. For this purpose, the moving average of +/- 12 hours for the district's electricity load profile is used to charge the EVs counter-cyclically to the district's electricity demand during a given hour in comparison to the moving average.

The dynamics of the EV charging profiles for the individual buildings conform to the profiles of the overall districts and are scaled according to the electricity requirements for electromobility in the respective building. This results in different electromobility load profiles for each district.

5.4.4 Heat load profiles, households

Demand for heating greatly depends on exterior temperatures. For reasons of simplification, the thermal load profile for the provision of space heating in residential buildings is developed using the heating degree days method and calculated for the hourly outdoor temperature curve. Night setbacks and heating periods are also taken into account. The heating limit temperature is set at 15°C for conventionally refurbished buildings (types B and F) and 12°C for buildings refurbished or constructed to the future-oriented standard (types L and K). The indoor temperature in both cases is 20°C. The heating load curve is proportional to the difference between the indoor and outdoor temperature for all days falling within the heating period on which the outdoor temperature is below the heating limit temperature; otherwise, it is zero. Figure 8 shows the normalized heating load profile for the older building types for one year.

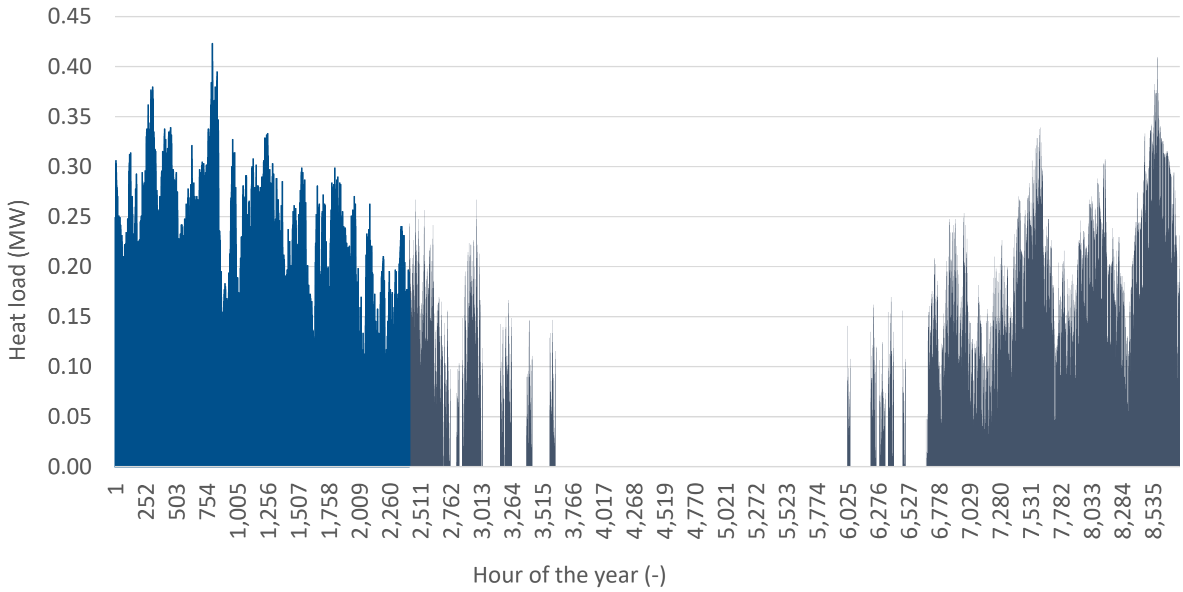


Figure 8 Normalized heat load profile for households of building types B and F

5.4.5 Domestic hot water load profiles for households in the district view

The decrease in domestic hot water is much more dynamic than the heating load curve and usually only occurs for short periods of significantly less than an hour. The modeling shows the hourly demand. Due to the consideration of the smearing of the hot water demand curve when aggregating many households, different load profiles are selected for the district approach (variant 1) and the individual approach (variants 2 and 3). For the district, the tap profiles from DIN 12831-3 are used, which specifies tap profiles for several households aggregated for single-family houses and multi-family houses (Deutsches Institut für Normung e.V. (DIN), 2017). These tapping profiles are the same for every day of the year. The load profiles are shown in figure 9.

5.4.6 Domestic hot water load profiles for households in the individual building analysis

Synthetic profiles calculated using the DHWcalc tool (Jordan and Vajen, 2005) are used to map peak loads for domestic hot water tapping for individual buildings. DHWcalc was developed as part of the Solar Heating and Cooling Program of the International Energy Agency (IEA-SHC), Task 26: Solar Combisystems. It calculates DHW tapping profiles on a statistical basis. As with DIN, a distinction is made between profiles for single-family homes and multi-family buildings, with the option of specifying the number of residential units. A sample tap profile for the first week of January for a single-family house is shown in figure 10. The load profile features strong load peaks at times when drinking water is tapped, while the volume of water falls to zero during certain periods in between.

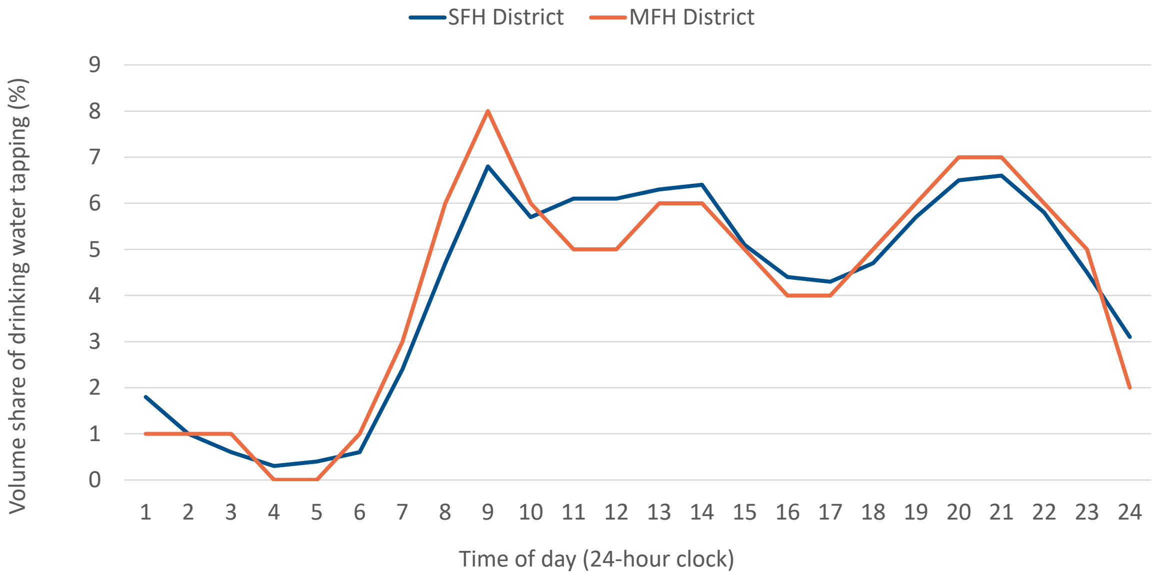


Figure 9 Volume shares of domestic hot water tapping distributed over the day for single-family homes (SFH) and multi-family buildings (MFH) in the district modeling

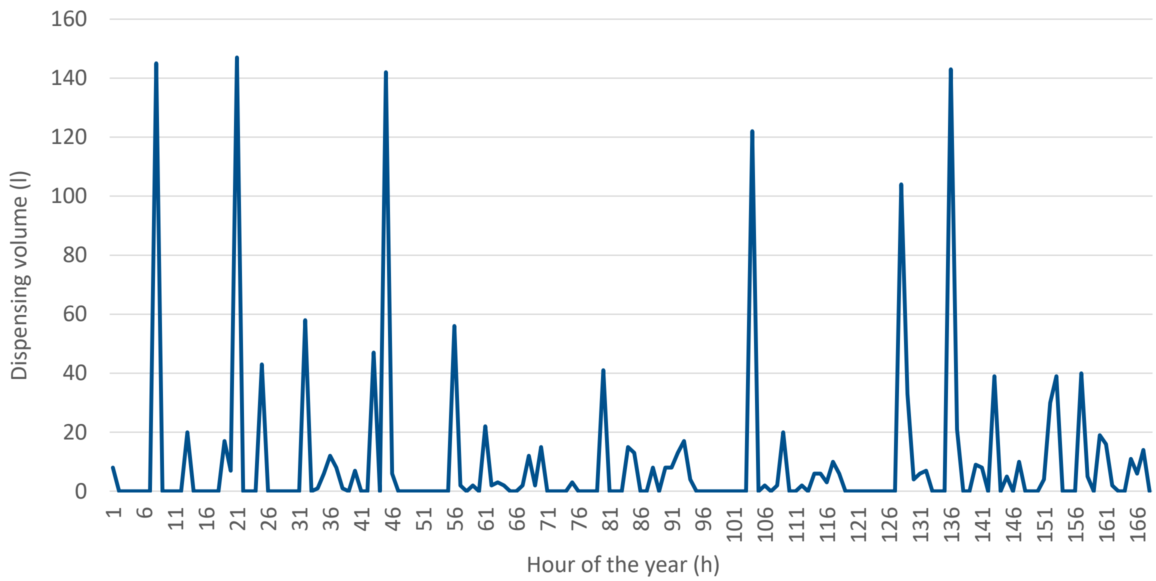


Figure 10 Drinking water tapping profile for a single-family home in the individual building view in the first week of the year

5.4.7 Heat load profile in the trade, commerce and services (TCS) sector

The load profiles in the TCS sector are determined using the BDEW methods for daily values (Bundesverband der Energie- und Wasserwirtschaft e. V. (BDEW) et al., 2016). The load profiles are based on the outdoor temperature and a distribution formula depending on the sector (households, TCS) and, in the TCS sector, on the type and distribution of annual energy over individual days. This method is supplemented by a further procedure that allows the daily values to be distributed over individual hours (Bundesverband der deutschen Gas- und Wasserwirtschaft (BGW), 2006). This distribution is also based on the outdoor temperature and differs for commercial buildings, single-family homes and multi-family buildings. The hourly load profiles obtained in this way for the heating requirements of TCS buildings are used both for the district approach (variant 1) and for the cases involving a decentralized supply of heat (variants 2 and 3) and are scaled according to these buildings' specific annual energy requirements. Figure 11 shows the load profile calculated in this way for office buildings in the MFH_L building type for one year with the statistical distribution over one day.

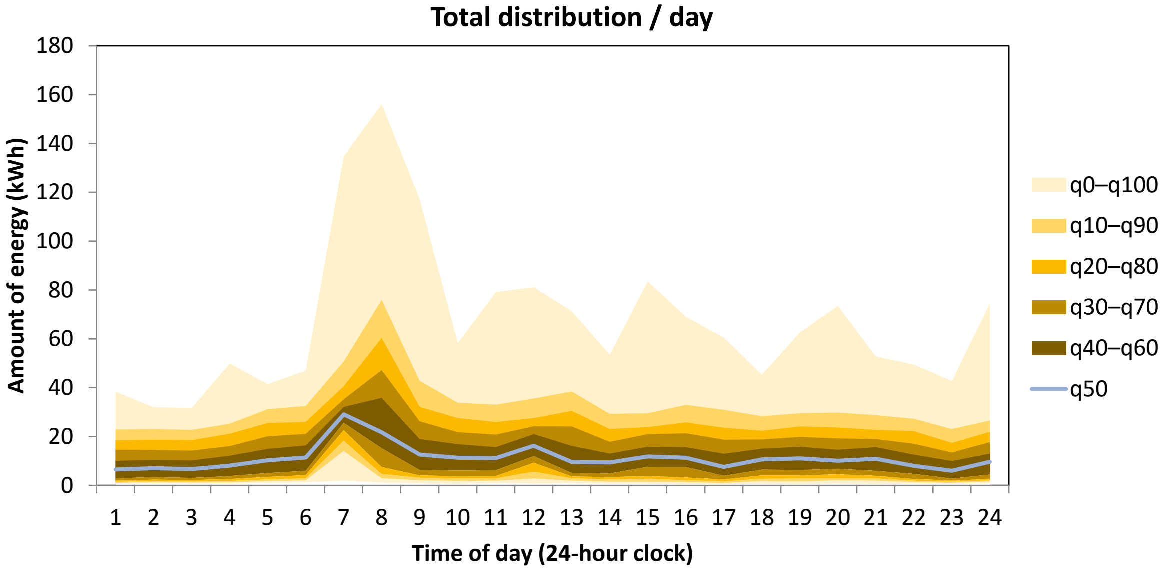


Figure 11 Total heat load profile for office buildings of building type MFH_L

5.4.8 Load profile, heating network losses

As shown in section 5.3.7, it is assumed that all districts have the same heating networks, and that these networks have annual network losses of 13 percent. These network losses are added to each hourly heat demand value in supply variant 1 for the districts. This results in a heat load profile for the heating network that is equivalent to 113 percent of the sum of the heat demand profiles of all buildings in the respective district in each time step. Within this methodology, the seasonality of heating network losses is ignored for the reasons mentioned in section 5.3.7.

5.5 Solar energy potential

The solar energy potential was calculated using the roof areas of the building types provided by the IWU typology (Institut Wohnen und Umwelt, 2015). In addition to the size of the roof, the usual roof shapes are also specified for the building types, but without indicating the proportions of the different roof shapes. The roof shape determines two things: the angle of inclination of the panels, and what proportion of the roof area can accommodate the installation of solar panels and solar thermal energy equipment. To allocate the roof area to the individual roof shapes, it is assumed that all roof shapes specified in (Institut Wohnen und Umwelt, 2015) are present in equal proportions. The selected building types have three different roof shapes: gable roof, mono-pitched roof and flat roof. The reference areas and the roof areas of all building types are listed in table 14.

	Building type	Buildings in the district (number)	Usable area per building (m²)	Roof area per building (m²)	Roof shape
District A	MFH_F – k	20	426	217	Gable or flat roof (cold roof)
	MFH_K – z	20	1,219	321	Gable, mono-pitched or flat roof
District B	SFH_F – k	20	158	183	Gable or flat roof
	SFH_K – z	20	160	132	Gable roof
District C	MFH_B – k	10	284	103	Gable roof
	MFH_K – z	10	1,219	321	Gable, mono-pitched or flat roof
	TCS sales outlet in MFH_B – k	10	284	103	Gable roof
	TCS Office in MFH_K – z	10	1,219	321	Gable, mono-pitched or flat roof
District D	MFH_L – z	20	1,219	321	Assumption: gable, mono-pitched or flat roof
	TCS sales outlet in MFH_L – z	10	1,219	321	Assumption: gable, mono-pitched or flat roof
	TCS Office in MFH_L – z	10	1,219	321	Assumption: gable, mono-pitched or flat roof

k = conventional refurbishment, z = future-oriented refurbishment

Table 14 Usable areas and roof areas of the building types as used to determine the solar potential according to (Institut Wohnen und Umwelt, 2015)

The same assumptions are made for the two pitched roof types, gable roof and mono-pitched roof, which means that their potential can be summarized. For pitched roofs, it is assumed that the pitch of the roof is 35°, 80 percent of the gross roof area can be used for the installation of solar systems, and this usable roof area is fully occupied by solar panels. In addition, equal distribution in the four cardinal directions is assumed. Solar panels can theoretically be installed in all four cardinal directions; the model assumes that the decision as to whether this is cost-effective is based on the incident solar radiation. For solar thermal energy, it is assumed that there are systems for heating support, including domestic hot water heating, and that these occupy 1 m² of module area per 10 m² of usable floor space. It is also assumed that equipment is installed facing south only (southwest to southeast) in order to achieve a sufficient solar yield in the transition period; the other three cardinal directions are not used for the installation of solar thermal energy. For flat roofs, an alternating installation of the solar arrays along the east–west axis with an inclination of 10° in each case is assumed, resulting in more effective utilization of the available roof area. In this case, solar panel area is 60 percent of the flat roof area. The maximum solar panel and solar thermal potential calculated for the four districts is shown in table 15; it is important to note that this potential cannot be aggregated, as competition for space has not been taken into account.

	Roof area, pitched roof (m²)	Roof area, flat roof (m²)	Photovoltaic potential (MW)	Solar thermal potential (m²)	Solar thermal potential (MW)
District A	6,405	4,350	1.93	3,193	1.89
District B	4,469	1,831	1.17	730	0.43
District C	6,294	2,183	1.59	2,908	1.72
District D	8,476	4,366	2.35	4,681	2.76

Table 15 Maximum photovoltaic and solar thermal potential in the four districts

5.6 Energy requirements and solar potential of the districts in comparison

The energy requirements of the districts are calculated by aggregating the energy requirements of the buildings, which differ according to building type, efficiency standard and type of use. The individual demand values can be calculated based on the input data used (see section 5.3). As figure 12 illustrates, the four districts have different energy demand densities. District B has the lowest energy demand across all energy sectors. It should be noted that all energy requirements represent net energy requirements and the heating requirements shown do not include heating network losses.

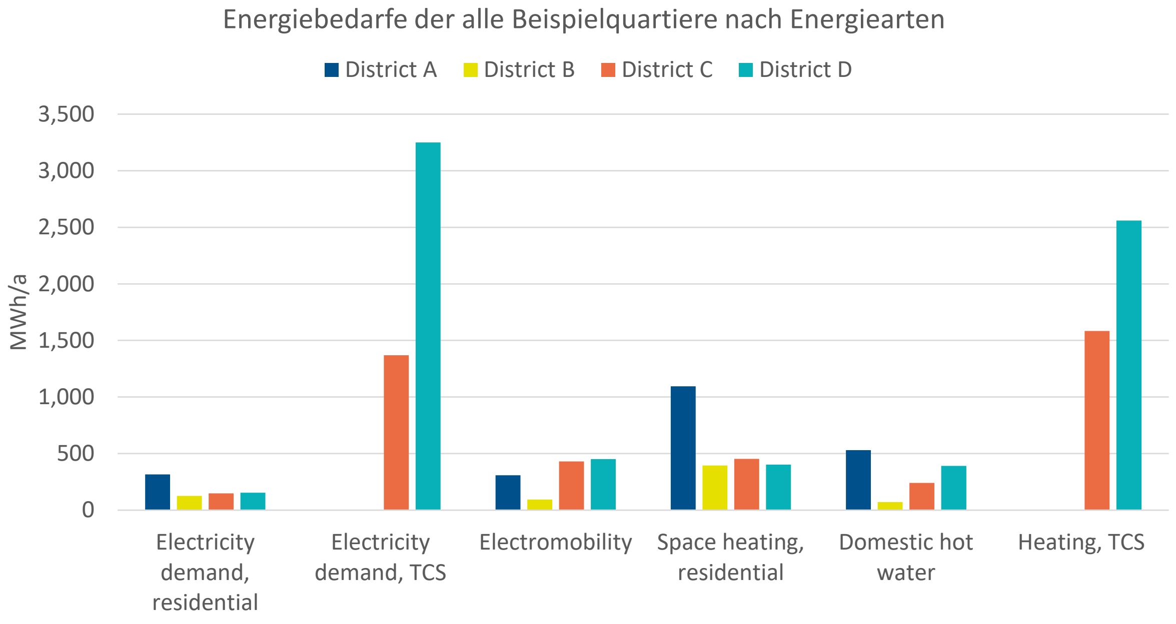


Figure 12 Energy requirements of the four sample districts in 2045

Figure 13 illustrates the distribution of energy requirements in the various districts. Significant differences in the composition of energy requirements between the residential and mixed districts become clear.

Figure 14 shows the net energy requirements of the districts in comparison to their maximum solar power generation when their photovoltaic potential is fully utilized. The energy requirements are divided into electricity and heating requirements. It can be seen that districts A and B achieve a higher ratio of maximum solar power yield to total energy demand than mixed districts C and D due to their lower energy demand density. How this higher ratio affects the degree of photovoltaic potential utilization and the degree of self-sufficiency of the districts is discussed in the results section of this brief study, in section 6 and especially subsections 6.2.1 and 6.3.2.

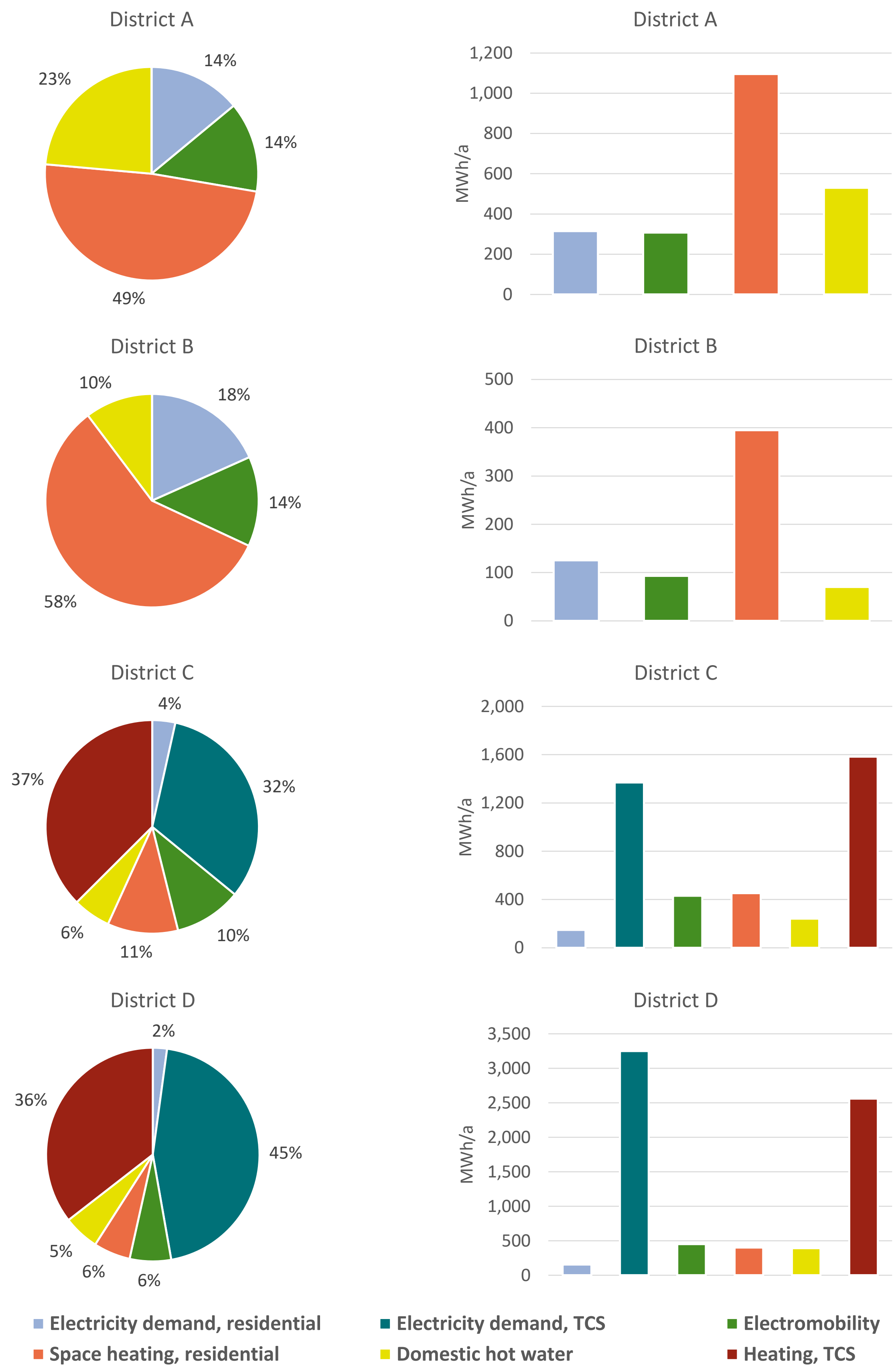


Figure 13 Distribution of energy requirements in all districts

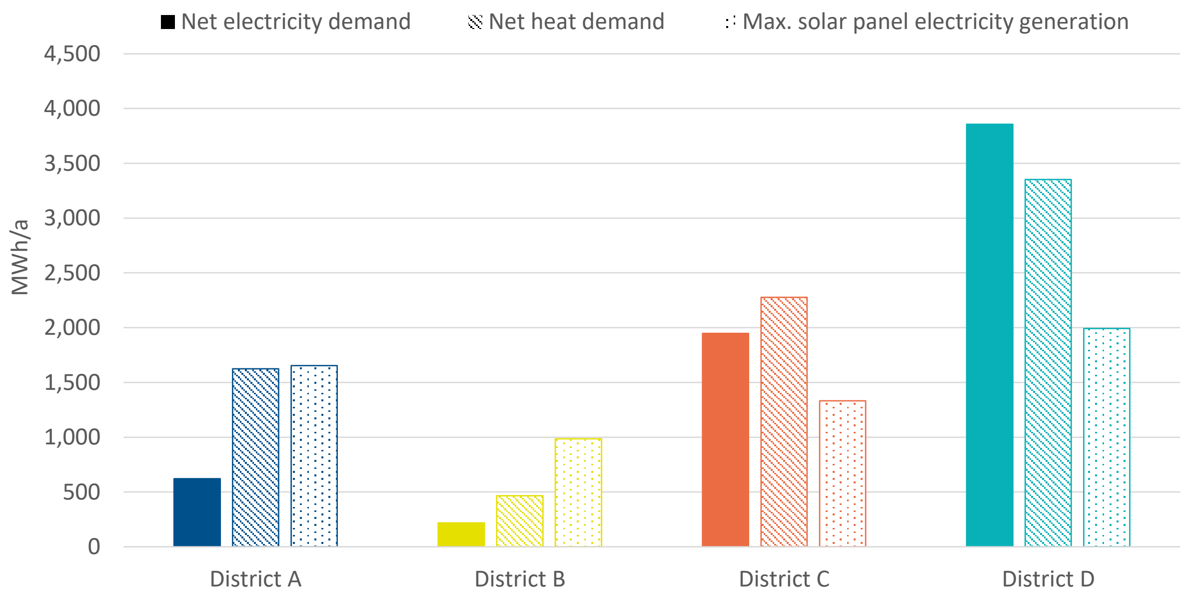


Figure 14 Net electricity and heat demand (without heating grid losses) for the four districts compared to the maximum solar power generation in the district with full utilization of the PV potential (solid: net electricity demand, shaded: net heat demand, dotted: maximum PV electricity generation)

5.7 Economic parameters

The assumptions made for the economic parameters have a direct influence on the results of the study, as the variant with the lowest total energy costs is calculated as part of optimization (see section 4). Table 16 lists the most important parameters used in the modeling, with all costs corresponding to present-day monetary value. The calculations are carried out for the target year of 2045, which is why the parameters must be projected for this target year. Among other things, an inflation-adjusted interest rate of 4 percent is assumed, which results in an annuity factor of 0.07358 for the 20-year period under consideration.

Electricity imports are expected to cost EUR 0.30/kWh, which is higher than the electricity generation costs of solar panels, wind energy and CHP. The result is that the use of renewable energy potential is preferred to electricity imports (see also the sensitivity analysis of the import electricity price in appendix B). An imported electricity price this high promotes self-sufficiency in the districts and thus facilitates comparison between the district approach and building optimization. It is assumed that electricity imports in the target year, 2045, will be climate-neutral, as will the energy supply to the districts.

The costs of exporting electricity come to EUR 0.30/kWh, meaning that payments must be made to export electricity. This determination is based on the assumption that a high proportion of fluctuating renewable energy will be present in the electricity grid in 2045, the target year. At times when the respective district generates a local electricity surplus, the surplus will consist of energy from solar panels and wind, both fluctuating renewable energy sources, and will occur at the same time as an electricity surplus from renewable sources in the surrounding energy system. Thus, the aim of setting an export electricity price in the modelling and energy system optimization is to prevent locally generated solar and/or wind power from additionally affecting the higher-level grid. Alternatively, curtailment of energy from solar panels and/or wind can be used at any time in the model; this is similar to cost-free or revenue-free exporting of electricity.

In simplified terms, it is assumed that all costs incurred for the development and operation of waste heat sources are included in the energy costs of the waste heat. For the potential of the waste heat, it is assumed that the maximum output of the waste heat can cover no more than 50 percent of the district's maximum heat demand. The annual amount of waste heat provided is also capped at 50 percent of the district's annual heat requirements, meaning that there are two limits to the use of waste heat.

Aside from the restrictions on the potential of solar panels and solar thermal energy as described in section 5.6, no potential limits are taken into account in the model for the other technologies. Their design is therefore based solely on the energy demand to be covered with regard to the minimum total costs of the technology mix (see section 4).

The same parameters were used for the heating networks in the four districts. For the 20-year period considered in the KomMod calculations, the annuity for the heating network is EUR 59,586.14 per year. This was calculated from the building connection costs of EUR 2,500 each (based on (Clausen, 2012)) for 40 building connections and network costs of EUR 300 per line meter (based on (Pfnür et al., 2016)) for 57 line meters per building connection (Pfnür et al., 2016) and an assumed useful life of 50 years for the network and 20 years for the building connections. The annual operating and maintenance costs amount to 2 percent of the investment costs (Pehnt, 2017) and therefore contribute EUR 15,680 to the annuity.

Technology	Service life (a)	CAPEX (EUR/kW)	OPEX, fixed (% invest/a)	Fuel and/or energy costs
Solar panels	28 I	576 I	2 I	–
Solar thermal	25 I	330 (EUR/m²) I	1.2 I	–
Large-scale HP, geothermal probe	20 I	425 II	1.3 I	–
Large-scale HP, waste heat	20 I	275 I	1.3 I	see waste heat
Small-scale HP, geotherm al probe	20 I	1,244 I	1 I	–
Small-scale HP, air	20 I	683 I	1 I	–
Booster HP	20 I	683 I	1 I	–
Heating rods	15 III	80 III	4 III	–
Central biogas CHP	20 I	503 I	2.5 I	EUR 0.08/kWh IV
Decentralized biogas CHP	20 I	1,425 I	3.0 I	EUR 0.08/kWh IV
Wood boiler	20 I	214 I	6 I	EUR 0.21/kg V
Li-ion battery	15 I	EUR 113/kWh I	1 I	–
Decentralized thermal storage	20 I	EUR 17.24/kWh I	1.3 I	–
Central thermal storage	40 I	EUR 1.55/kWh I	1 I	–
Waste heat	–	–	–	EUR 0.015/kWh VI
Imported electricity	–	–	–	EUR 0.30/kWh
Wind power (imported, PPA)	26 I	1,335 I	3 I	EUR 0.05/kWh additional PPA surcharge
Exported electricity	–	–	–	EUR 0.30/kWh

I (Sterchele et al., 2020); II (Fraunhofer Institute for Solar Energy Systems ISE (Fh ISE), 2021); III (Foster et al., 2020); IV based on (Reinholz and Völler, 2021); V (Duić et al., 2017); VI Analysis from (Federal Ministry for Economic Affairs and Energy (BMWi) and Federal Ministry of Education and Research (BMBF), 2021)

Table 16 Overview of the economic parameters used for the energy sources/components considered

6 Calculation results

6.1 Results for individual districts

The results of the optimization calculations for the four districts, with the variants examined, are presented and discussed below. For reasons of clarity, the calculated time series are not presented.

6.1.1 District A

District A is characterized by dense development with exclusively residential use in an urban environment. Figures 15 and 16 show the results of the cost-optimized supply for variant 1 (district-optimized with electricity and heat exchange between the buildings), variant 2 (mixed, no heating network) and variant 3 (optimization at the building level only). Figure 15 shows the installed electrical output (left graph) and the resulting electricity generation (right graph) for all three supply variants. Solar panels account for the largest share of electricity generation, at 43 percent in variant 1, 46 percent in variant 2 and 55 percent in variant 3. CHP and wind power can also be used in variant 1, which means that only 1 percent of the electricity requirement has to be imported. As no CHP is available in variant 2 due to the decentralized supply of heat, the proportion of wind power used increases by 8 percent from variant 1 to variant 2, to a total of 40 percent. In addition, more electricity has to be imported in variant 2 (14 percent of the total electricity requirement). No wind power is available in variant 3, either, and imports here increase to a share of 45 percent. The electricity exceeding the net electricity demand is mainly used for heat pumps, while storage losses from electrical storage systems account for a small portion.

When comparing the installed capacity with the amount of electricity generated by solar panels, it can be seen that the installed capacity increases significantly more from variant 1 to variant 3 than the amount of electricity generated, which is due to the fact that the curtailment of PV electricity gradually increases. The curtailment of the systems in the various scenarios is discussed in section 6.2.2. The difference between electricity generation and net electricity demand is the electricity required for the heat pumps and the losses in the battery storage systems.

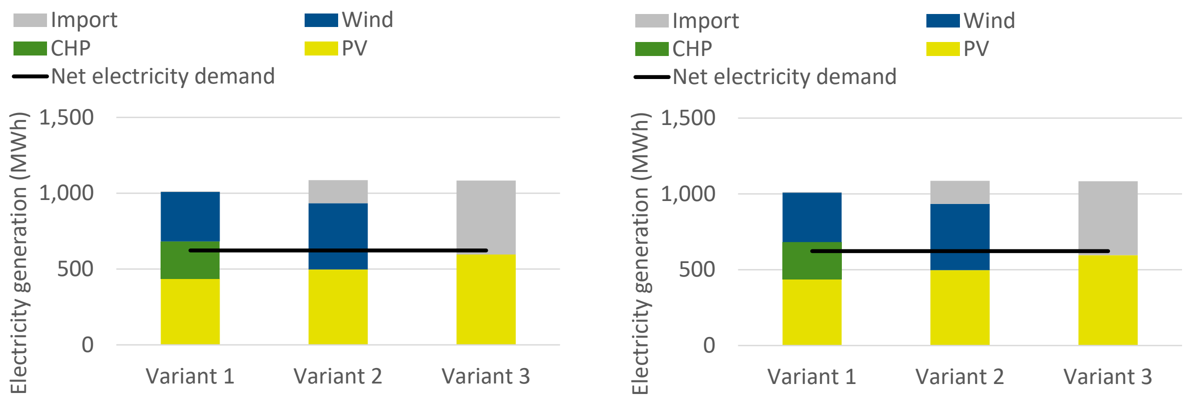


Figure 15 Installed electrical output (left) and annual electricity generation (right) for the supply variants in district A

Figure 16 shows the installed thermal output (left graph) and the thermal energy generated (right graph) for the three supply variants in district A. Heat pumps are the predominant generation technology in all three variants. What is more, in variants 2 and 3, the two supply variants with decentralized heat supply, it is actually the only generation technology, covering 100 percent of the demand for heat. The differences between net heat demand and heat generation shown in the heat generation figures are due to energy losses in the thermal storage systems, which are negligible in district A. In variant 1, the heat generated from the CHP units is also available. In order to achieve a design of the supply systems that is adapted to the district, exporting electricity is penalized in these scenarios by applying export costs (see section 5.7). This means that CHP run time is limited by the use of electricity in variant 1. Furthermore, heat generation is 13 percent higher in variant 1 than in variants 2 and 3, as losses of this amount were assumed for the heating networks (see section 5.3.7).

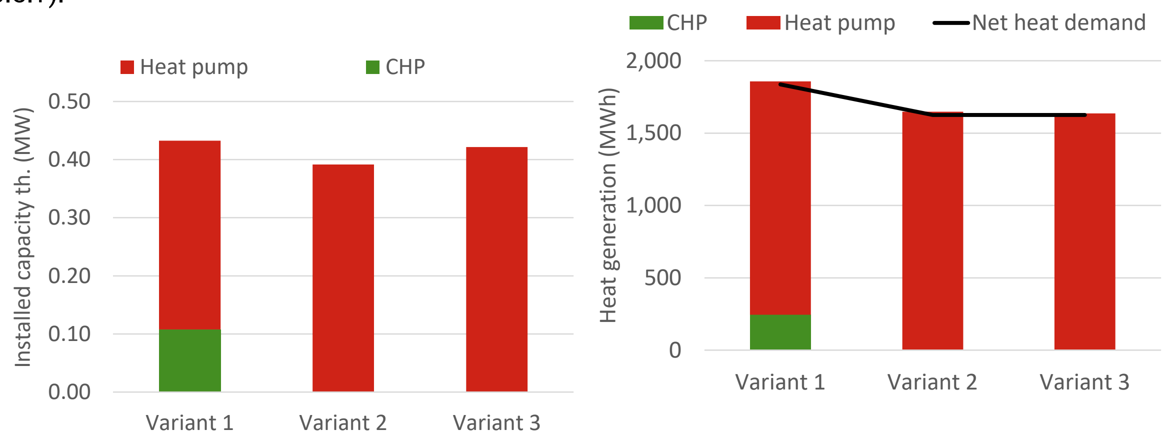


Figure 16 Installed thermal output (left) and annual heat generation (right) for the supply variants in district A

In addition to the installed capacity and energy generation volumes of the various scenarios, the installed storage capacity and energy costs are two other important results of the study. Figure 17 shows the installed storage capacity (left graph) and the specific energy costs (right graph) for district A. The storage volumes result from the optimization of the energy systems (see section 4). It is apparent that the installed battery capacity increases from variant 1 to variant 3 due to the increasingly decentralized energy supply structure, going from 0.82 MWh in variant 1 to 1.20 MWh in variant 3. This trend is caused by the increase in installed photovoltaic capacity. In variant 3, the installed battery capacity corresponds to decentralized battery storage capacity of around 30 kWh per MFH. This battery storage capacity can be installed both as home storage and in the context of bidirectional charging of electric vehicles.

The amount of thermal storage gradually decreases from variant 1 to variant 3. For example, the central thermal storage in variant 1 has a volume of around 121 m³ (or 120,916 l), while in variant 2 the storage volume per building is around 2,600 l and in variant 3, the figure per building is 1,488 l for MFH_F and 1,993 l for MFH_K. The decrease in heat storage volumes as the energy supply structure becomes increasingly decentralized can be explained by the rising proportion of imported electricity that is freely available at any time, with the result that the decentralized heat pumps can be operated flexibly according to the heat demand profile and there is thus less need to store thermal energy temporarily. In addition, the CHP units used in variant 1 simultaneously generate both electricity and heat, with the result that thermal storage capacity is used to compensate for the temporal offset between heat generation and demand, which makes more economic sense overall than curtailing central heat generation in the CHP units. A more detailed discussion of the storage volumes can be found in appendix B.

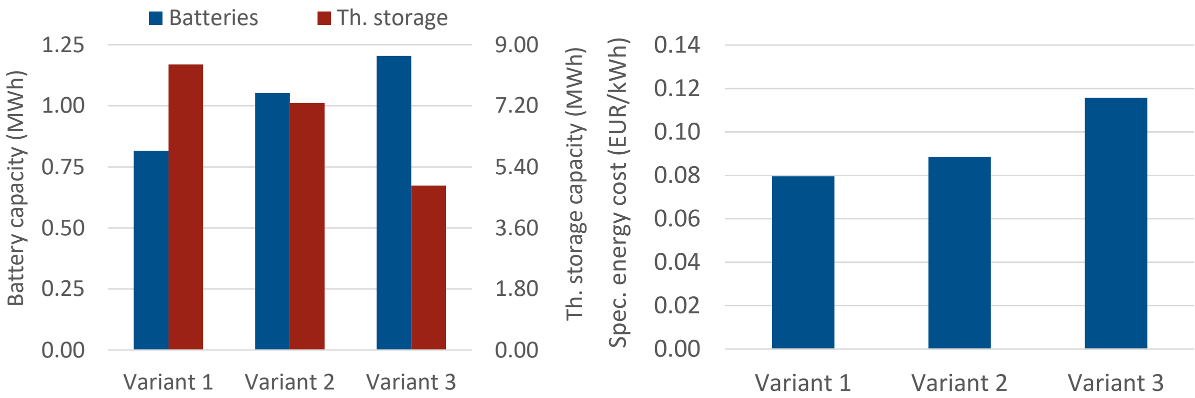


Figure 17 Installed storage capacity (left) and specific energy costs (right) for the supply variants in district A

The graph on the right in figure 17 shows the specific energy costs of the three supply variants as average costs of the respective total energy demand for electricity and heat. It is apparent that the centralized supply structure of variant 1 results in significantly lower costs, at 8.0 cents/kWh, than the supply structure in the mixed variant 2, at 8.6 cents/kWh, and especially in the decentralized variant 3, where costs stand at 11.6 cents/kWh. There is a moderate increase in the specific energy costs in variant 2 due to the decentralized organization of the thermal supply structure in contrast to variant 1. The completely decentralized energy supply in variant 3 (building optimization) has the highest costs. Section 6.3.1 shows the exact composition of the specific energy costs and compares the different districts.

6.1.2 District B

In district B, as in district A, solar panels, wind and CHPs are all available as electricity generators (see figure 18), but the CHPs in this rural district are operated with wood pellets instead of biogas. In variant 1, CHPs serve 53 percent of the demand for electricity, while 47 percent is covered by solar panels. Wind power is not used in variant 1, as solar panels and CHPs are the cheaper electricity generators. Wind power is more expensive because in addition to the pure costs of generating electricity, a further 5 cents/kWh must be taken into account for grid fees and the remuneration due under a PPA contract. In variant 2, in which no CHP is available due to the decentralized heat supply, wind energy accounts for 33 percent of the electricity supply, and electricity imports also increase to 5 percent. In variant 3, in turn, solar panels and imports are the only available electricity sources (wind power PPA contracts are not expected at the level of individual buildings), with solar panels accounting for a larger share, at 72 percent, than in variant 3 in district A. As can also be observed in district A, installed solar panel capacity rises at a sharper rate with the increasing decentralization of the energy supply structure than does the amount of electricity demand covered by solar panels, as curtailment increases (see sections 6.2.1 and 6.2.2).

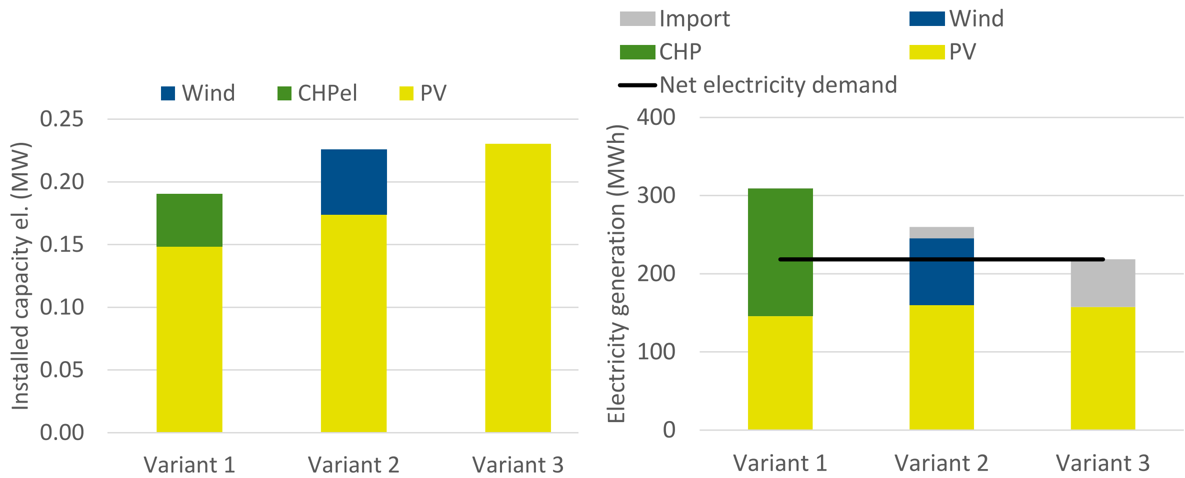


Figure 18 Installed electrical output (left) and annual electricity generation (right) for the supply variants in district B

While heat pumps represent the dominant heat generation technology in district A, wood boilers, which are permitted in rural districts, are predominant in district B (see figure 19). In variant 1, biomass can be used in the CHP units or in a wood boiler. However, the sole use of CHP units as a fuel-based energy source instead of the use of wood boilers as a peak load technology for the heat supply makes more sense from an overall economic perspective. Consequently, wood boilers are only used in variants 2 and 3. Since the CHP units in variant 1 have a limited service life due to the use of electricity, the proportion of heat pumps is significantly higher in variant 1 than in variant 2. It should also be noted that the use of technology with unrealistically low outputs was excluded, with the result that in variant 3 wood boilers are the sole heat supply technology and a low installed capacity of heat pumps or solar thermal energy was excluded. It should also be mentioned that supplying heat to rural areas based solely on biofuels is generally not conducive to a climate-neutral energy supply due to the limited availability of sustainable biofuel quantities. This means that the extensive use of heat pumps is also an option here.

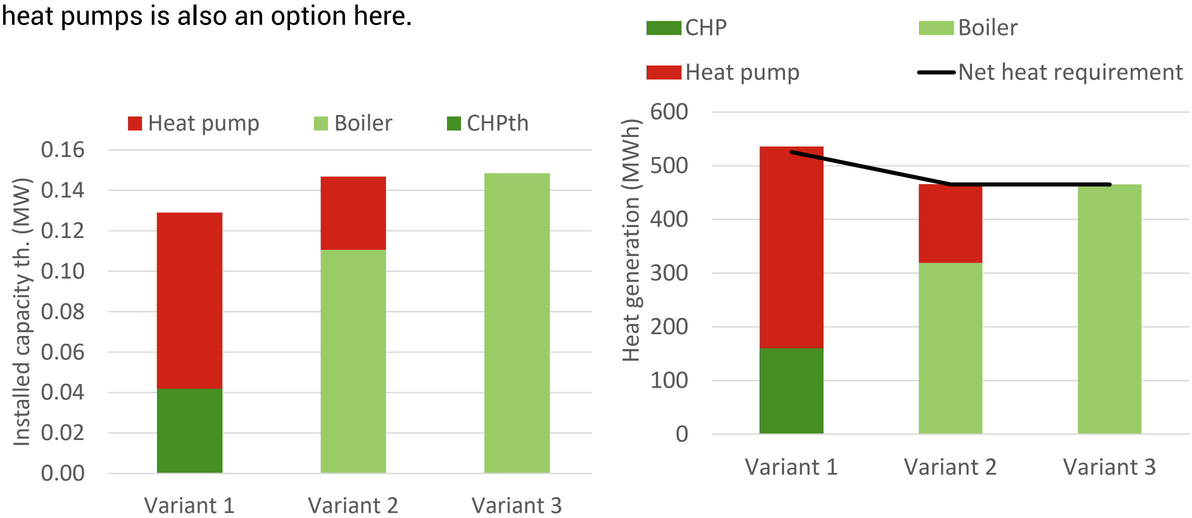


Figure 19 Installed thermal output (left) and annual heat generation (right) for the supply variants in district B

The battery capacity shown in figure 20 (left graph) for district B follows the same trend as in district A, in that installed battery capacity increases successively with the increasing decentralization of the supply structure. Here, too, this trend is caused by the increase in installed solar power from variant 1 to variant 3. In variant 3, battery capacity is around 13 kWh (SFH_F) and 16 kWh (SFH_K) per building. A look at the thermal storage capacity shows that variant 1 has by far the highest storage capacity, at 3 MWh or around 43 m³. This difference from the other variants is caused by the fact that heat pump operation is adapted to the fluctuating solar electricity generation and by the CHP units' role in generating electricity, which is why, as in district A, larger installed thermal storage capacity makes more economic sense overall. Thermal storage capacity in variant 3 stands at 102 l (SFH_F) and 148 l (SFH_K) per building.

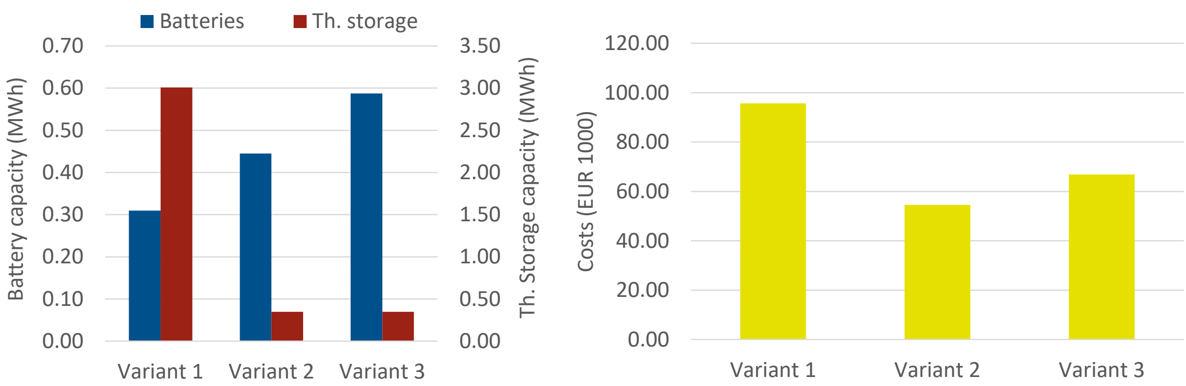


Figure 20 Installed storage capacity (left) and specific energy costs (right) for the supply variants in district B

Variant 1 has the highest specific energy costs in relation to energy demand (see figure 20, right-hand graph). This is due to the high costs associated with the heating network itself, which is not worthwhile from an economic perspective given the comparatively low heat demand density in the more-rural district B (a more detailed breakdown of the costs can be found in section 6.3.1). The most cost-effective option for district B is variant 2, which involves a decentralized supply structure for heat and a centralized one for electricity, while the costs of the completely decentralized supply envisaged in variant 3 lie between those of variants 1 and 2.

6.1.3 District C

Solar panels, biogas-powered CHP units (centralized in variant 1 and decentralized in variants 2 and 3), regional wind energy and imports are available as electricity sources to supply the urban mixed district C, which consists of existing buildings. As figure 21 shows, solar panels account for the largest share of the electricity supply in variant 1, at 42 percent, while regional wind potential is used and accounts for a larger share, at 34 percent, than CHP units at 24 percent. Electricity imports are of marginal significance. The share of electricity demand served by CHPs increases significantly in variant 2, to 63 percent, while imports amount to 1 percent and wind energy is not used. This is due to the composition of the decentralized heat supply, which increasingly relies on CHPs as the main heat source and also leads to a higher total electricity demand in variants 2 and 3 compared to variant 1 (see figures 21 and 22). CHPs account for the same share of the electricity supply in variant 3, at 63 percent, while solar panels drop to 27 percent and electricity imports increase to 10 percent, to take account of the fact that the electricity supply is decentralized and electricity cannot be exchanged between buildings. It is also evident that solar panel potential is used less in variant 3, which is also reflected by the fact that installed power decreases to 1 MW. In addition, a comparison between installed CHP output and the amounts of electricity produced by CHPs reveals that variant 3 exhibits the most full load hours, averaging approximately 3,565 h, while CHPs have the fewest full load hours in variant 1, at 2,001 h, due to the high proportion of fluctuating renewable energy sources.

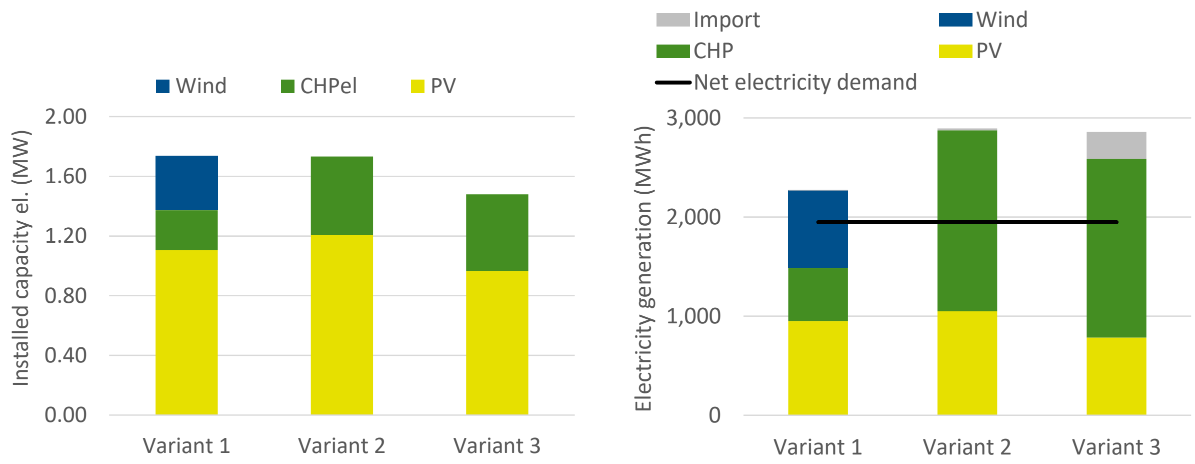
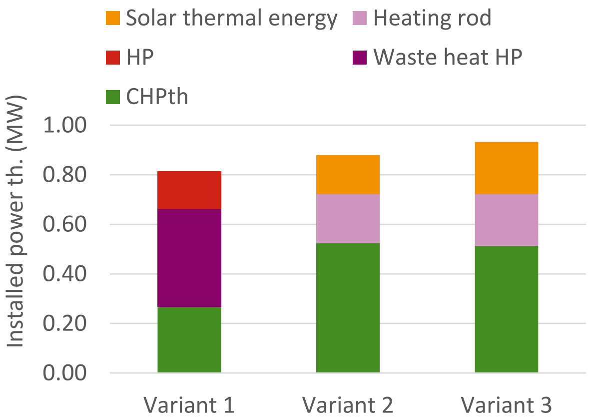


Figure 21 Installed electrical output (left) and annual electricity generation (right) for the supply variants in district C

In variant 1, waste heat is available at a temperature level of 40°C to supply heat to district C. This waste heat is brought up to the heating network flow temperature of 70°C by means of heat pumps and then fed into the network. The waste heat is identified as an advantageous heat source in the overall system optimization, and its full potential to supply a maximum of 50 percent of the total annual heat consumption is utilized (the waste heat output does not exploit the potential of 50 percent of the maximum heat demand). As figure 22 (right-hand graph) shows, a heat pump connected to the waste heat source covers a total of 57 percent[2] of the demand for heat, with a COP of around 8, while a separate, central brine heat pump provides 23 percent and the CHP units 21 percent. The heat pump connected to the waste heat achieves 3,728 full load hours and therefore does not use the waste heat potential consistently throughout the year. The option of using additional heating rods as a peak load technology for the heating network in variant 1 is not used. No waste heat is available in variants 2 and 3, as there is no heating network. As a result, the CHP units make an increased contribution to the heat supply, supplemented by heating rods and solar thermal energy, in both decentralized heat supply variants. It is important to note here that, as described in section 3.2 and shown in table 2, heat pumps cannot be used on a decentralized basis in district C. Compared to variant 2, the completely decentralized supply variant 3 has higher installed capacity and volume of heat generated by solar thermal energ



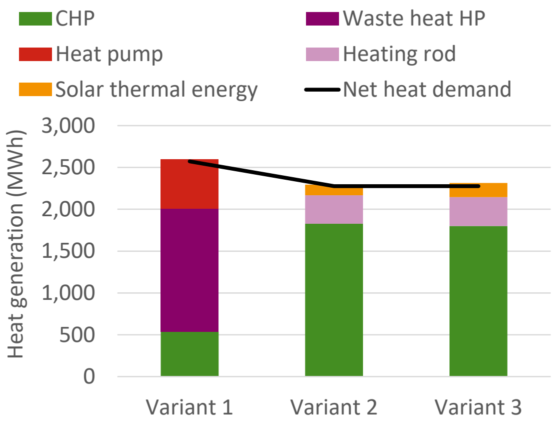


Figure 22 Installed thermal output (left) and annual heat generation (right) of the supply variants in district C

As shown in Figure 23 (graph at left), battery capacity decreases as the energy supply is increasingly organized on a decentralized basis. While variant 1 has battery capacity of 1.63 MWh for district C, between 21 and 42 kWh of decentralized battery capacity per building (median value 26 kWh per building; total 1.05 MWh for the district) is built up in variant 3. This trend is caused by the successively lower proportions of fluctuating renewable electricity generation in variants 2 and 3. Furthermore, variant 1 has the largest central heat storage volume, at 148 m³, owing to the high proportion of solar panels and wind power generation, so that the excess electricity generated by the fluctuating renewable sources can be stored in the interim as thermal energy by means of heat

[2] As the waste heat potential is limited to 50 percent of the energy demand, the heat pump connected to the waste heat can provide a higher proportion than 50 percent, which is influenced by the heat pump's COP.

pumps. In variant 2, the installed decentralized thermal storage averages 2,088 l per building. Owing to the higher proportion of solar thermal energy, variant 3 has higher storage volume per building, averaging 2,865 l. In variant 3, the newer building types have higher storage volume due to their load profiles. In addition, commercial buildings also have higher storage volume compared to residential buildings of the same building type, as they need more energy (see Figure 12).As in district A, the central energy supply structure is the most cost-effective alternative in district C, while variant 3 is the most expensive, as shown in figure 23 (right-hand graph) based on the specific energy costs in relation to energy demand. The significant difference between the specific energy costs of variant 1 and variant 2 is mainly due to the availability and integration of the waste heat potential into the centrally organized heat supply infrastructure in variant 1.

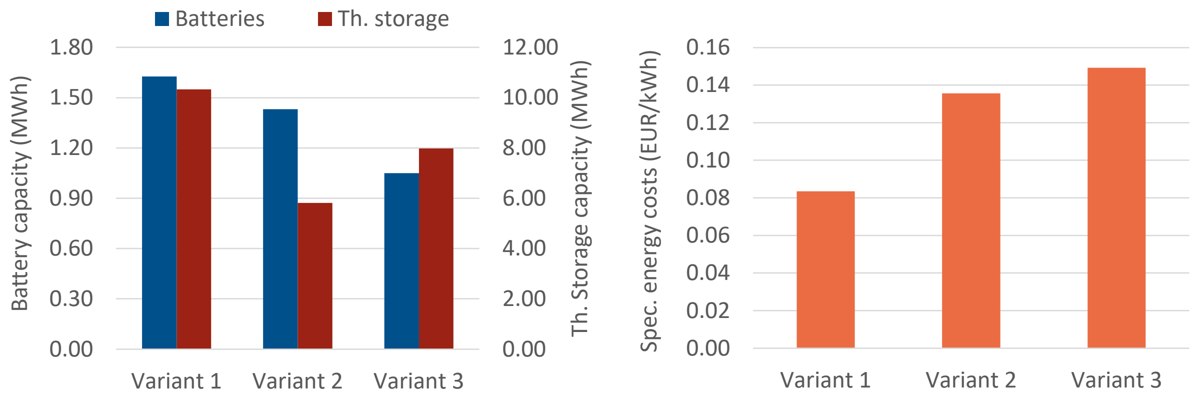


Figure 23 Installed storage capacity (left) and specific energy costs (right) for the supply variants in district C

6.1.4 District D

At approx. 4,000 MWh, electricity demand is highest in district D, which is made up of new construction and is partly commercial in nature (see figure 12). Solar panels make up between 42 percent (variant 1) and 28 percent (variant 3) of the power supply, with the share decreasing from variant 1 to variant 3 (see figure 24, right-hand graph), compared to the increase seen in districts A and B. Wind power makes up an equal share in variants 1 and 2, at 44 percent, while solar panels account for 42 and 39 percent, respectively. The remaining demand for electricity is covered by electricity imports in both variants, as no CHP units are permitted in district D (see section 3.2). Purchasing wind energy is not permitted in variant 3, which increases electricity imports. Because exchanging electricity between buildings is not permitted here, the installed PV output and the resulting PV electricity generation are significantly lower. The commercially used buildings have significantly higher electricity needs than the buildings with residential use. As a result, more PV electricity can be used in the commercial buildings than can be generated in the area available on the buildings' own roofs, which causes solar panels to account for a higher share of the electricity demand in the commercial buildings. The residential buildings, on the other hand, cannot utilize their full solar potential themselves due to their lower energy demand density, which is why significantly less PV power is installed in variant 3, as the residential buildings cannot make their unused solar potential available to the commercial buildings. This means that in district D, the different structure of the building types and the associated energy demand profiles make the possibility of exchanging PV electricity between the buildings in the district particularly advantageous and significantly reduces the need for electricity imports.

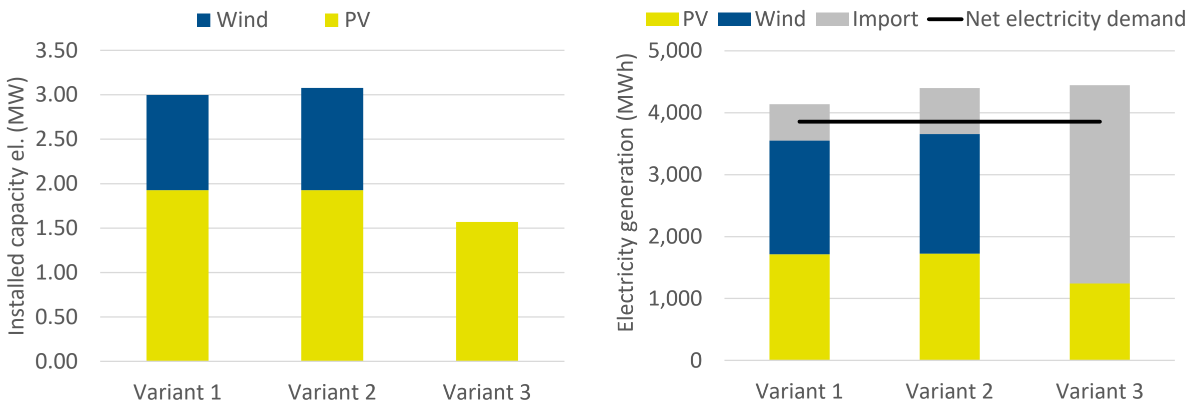


Figure 24 Installed electrical output (left) and annual electricity generation (right) for the supply variants in district D

On the heating side, waste heat is available at a temperature level of 40°C as a central supply technology in variant 1. Its contribution can cover a maximum of 50 percent of the annual heat demand and 50 percent of the maximum heat demand output due to the overall conditions that have been set (as in district C). The potential of installable waste heat output is fully utilized. As figure 25 (right-hand graph) shows, in addition to waste heat, additional heat pumps, a heat pump connected centrally to the grid, and decentralized booster heat pumps in the buildings cover the heat demand. The heating network in variant 1 is operated at a flow temperature of 40°C, which is sufficient to supply the buildings in district D with space heating. In addition to a central large heat pump, booster heat pumps are installed in each building. These raise the network temperature for the domestic hot water supply from 40°C to 70°C. It should be noted that the waste heat potential is not used consistently over the course of the year, but rather variably, and that it has 2,163 full load hours. In variants 2 and 3, the heat supply is based entirely on decentralized heat pumps, which provide both space heating (40°C) and domestic hot water.

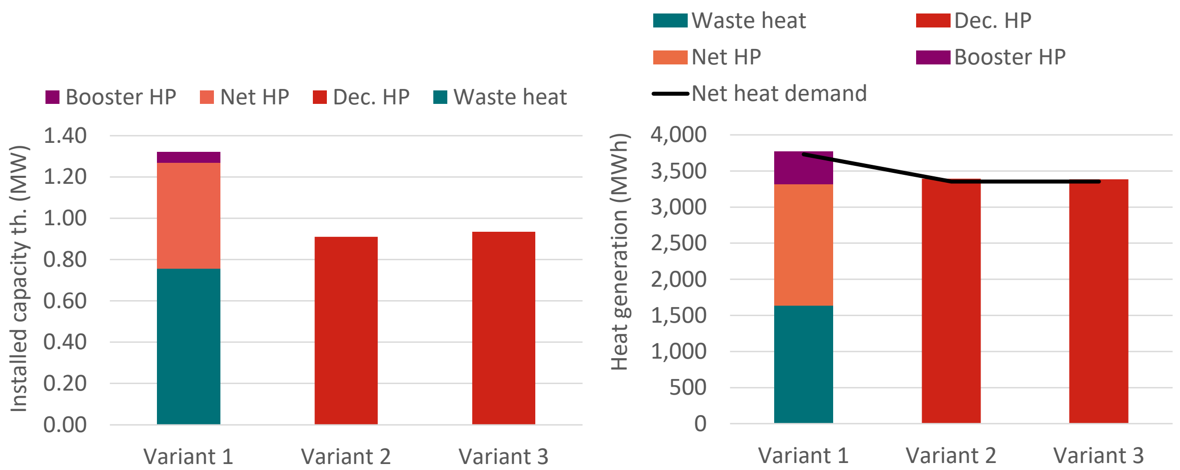


Figure 25 Installed thermal output (left) and annual heat generation (right) for the supply variants in district D

As the energy supply structure becomes more decentralized, both battery capacity and thermal storage capacity decrease (see figure 26, left graph). This results from the successively increasing quantity of imported electricity and the low proportion of solar power in variant 3. Decentralized battery capacity amounts to 28.5 kWh on average in variant 3. Higher volumes of imported electricity available flexibly on demand also increase the flexibility of heat pump operation, with the result that there is also no need for as much thermal storage capacity. In this way, the volume of decentralized thermal storage in variant 3 is between 2,669 l (residential use) and 11,445 l (retail outlets). Here, too, the commercial buildings have significantly larger storage volumes. The storage volumes calculated as a result of the optimization in variant 1 are mainly distributed over the central storage for the heating network operated at 40°C (500 m³), while decentralized buffer storage tanks with a volume of 216 l per building are calculated. Appendix B examines the sensitivity of the scenario results with regard to the size of the thermal storage using district D as an example.

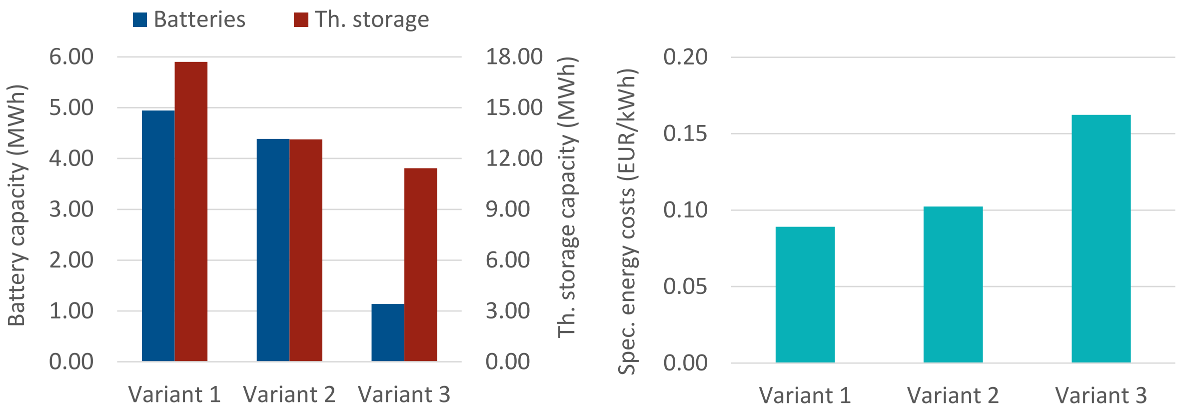


Figure 26 Installed storage capacity (left) and specific energy costs (right) for the supply variants in district D

The specific energy costs in relation to energy demand show the same trend in district D as in districts A and C and are lowest with a centralized energy supply, rising with greater decentralization. The 82 percent increase in energy costs from variant 1 to variant 3 is caused by the sharp rise in the use of imported electricity and the lack of waste heat potential.

6.2 District comparison

This section compares selected results for the variants of the four districts in order to identify and analyze general trends between the districts.

6.2.1 Utilization of solar panel potential

Figure 27 compares the rate of utilization of photovoltaic potential for all districts and variants examined, distinguishing between area-related and energy-related utilization rates. While the area-related degree of utilization indicates how much of the installable solar power is installed within the optimization calculations, the energy-related degree of utilization indicates the proportion of the solar power generation theoretically available as a result of the installable potential that is actually used for the power supply. The discrepancy between the two potential utilization rates thus reflects the curtailed solar electricity generation for each variant examined.

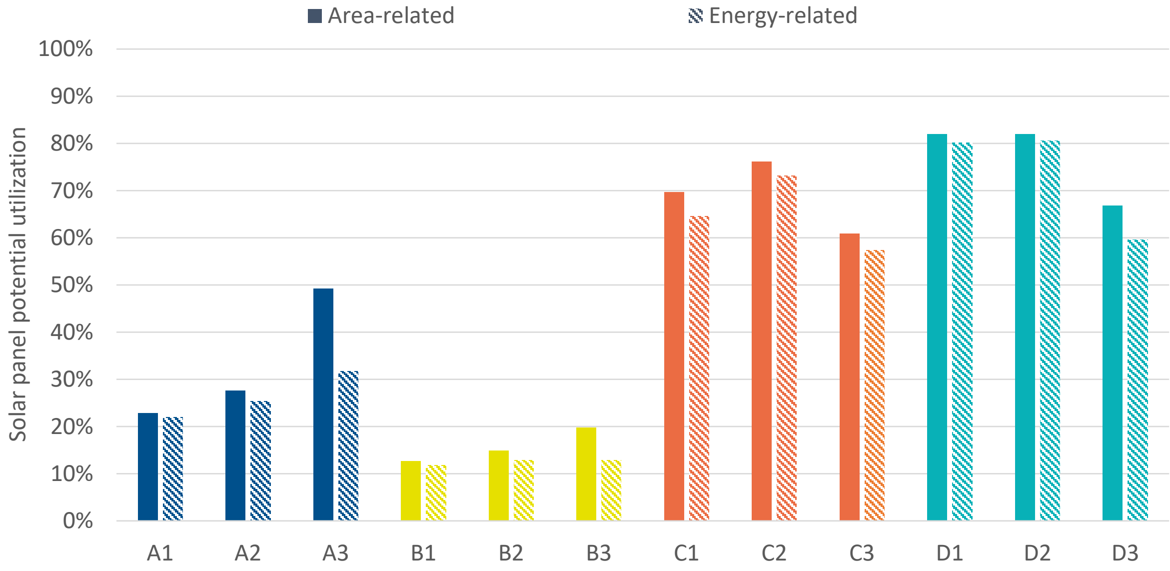


Figure 27 Area-related and energy-related utilization rates of the solar panel potential (bars in solid: area-related, shaded: energy-related)

The comparison between the districts in figure 27 shows that the solar utilization rate increases with increasing energy demand density in the districts (see figure 12). In addition, the degree of utilization in districts A and B increases from variant 1 to variant 3, as first the elimination of the CHP units (from variant 1 to variant 2) and then the elimination of wind energy potential utilization (from variant 2 to variant 3) must be compensated for in order to avoid further electricity imports. However, this higher utilization of PV potential is accompanied by greater curtailment, as the comparison between the respective energy-related and area-related solar potential utilization levels shows. Due to greater installed solar capacity, solar power surpluses occur at times. As exporting electricity is penalized by export costs (see section 5.7), the curtailment of solar electricity generation is preferred for purposes of optimization, although this increases the specific electricity generation costs of solar panels.

Another important aspect of the utilization of solar panel potential is the distribution of installed PV power within the districts. For example, the commercial buildings in the mixed districts C and D have higher utilization rates for variant 3 than the residential buildings, as they have a higher energy demand density and it is not possible for solar power to be exchanged between the buildings in the district. While the commercial buildings utilize their photovoltaic potential to a large degree or even completely in variant 3, the residential buildings can utilize a much smaller part of their PV potential than in variants 1 and 2, as they cannot make the solar power available to others.[3] This reduces the utilization of solar panel potential for the entirety of districts C and D in variant 3.

[3] According to the EU's Renewable Energy Directive (RED II, 2018/2001), Member States must, in the future, create a framework for renewable energy communities that allow them to exchange electricity with each other (European Union, 2018). Transposition of this directive will therefore enable variants 1 and 2 in a district, where only variant 3 is currently possible for regulatory reasons.

Furthermore, figure 27 clearly shows that the degree of utilization of solar potential increases as the districts' energy demand density rises, as the only way to compensate for the higher energy demand is through greater utilization of all available potential (solar, wind, biofuel CHP). This proves that the exchange of locally generated energy within a district and, above all, shared use of local solar panel potential become more important with increasing and/or heterogeneously distributed energy demand density and lead to greater utilization of local solar panel potential.

6.2.2 Curtailment of energy

Figure 28 shows the percentage of curtailed energy for three technologies — solar, wind and CHP (thermal) — for the different districts and variants. For CHP units, the curtailment of electrical energy generation is ruled out in the model, while the thermal energy generation of centrally operated CHP units can be curtailed.[4] Thermal energy from CHP units is only curtailed to a very small extent and amounts to a maximum of 1.7 percent in variant B1. Significantly higher proportions of curtailed energy are observed for electricity from solar panels and wind power, up to 35.5 percent for solar and up to 46.9 percent for wind. Curtailment increases the specific production costs for the electricity generated, as less electricity is generated even as the fixed costs remain the same. As the costs of importing electricity are comparatively high, curtailment of power generation at times is nevertheless preferred to importing electricity in some cases.

This brief study does not consider any other possible uses for surplus electricity. For example, it may be possible to use unusable electricity in the future for the production of hydrogen or other synthetic fuels instead of curtailing it. Appendix A shows the quantities of all curtailed energy generation for the variants examined.

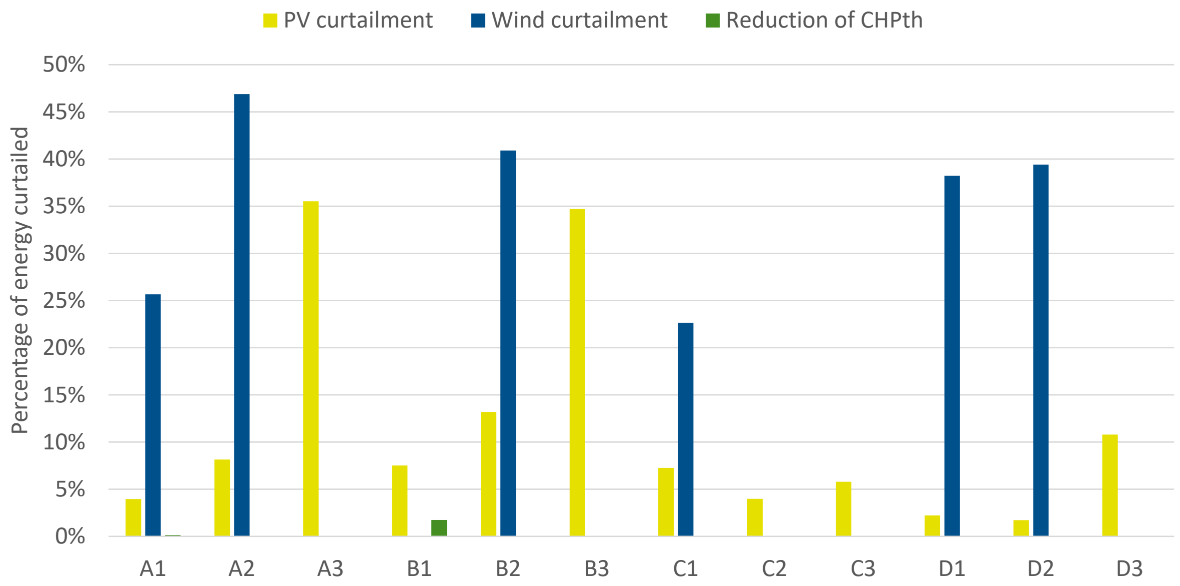


Figure 28 Percentage of energy curtailed in all districts and variants for solar, wind and CHPs (thermal)

[4] When the heat generation of CHP units is curtailed, the unused thermal energy is released into the environment by cooling the CHP unit.

As shown in figure 28, the percentage of solar power generation that is curtailed in districts A and B increases with the increasing decentralization of the supply from variant 1 to variant 3. At the same time, the installed solar panel output increases in order to compensate for the elimination of CHPs (from variant 1 to variant 2) and, in variant 3, also the elimination of wind energy, but large parts of the solar power cannot be utilized. This is further illustrated by figure 29, which shows the absolute amount of PV electricity generation that is curtailed. However, the higher utilization of solar panel potential in variant 3 for districts A and B and the associated high curtailed solar power yields make sense from the perspective of the district as a whole, as electricity imports and the costs associated with them can be limited in this way.

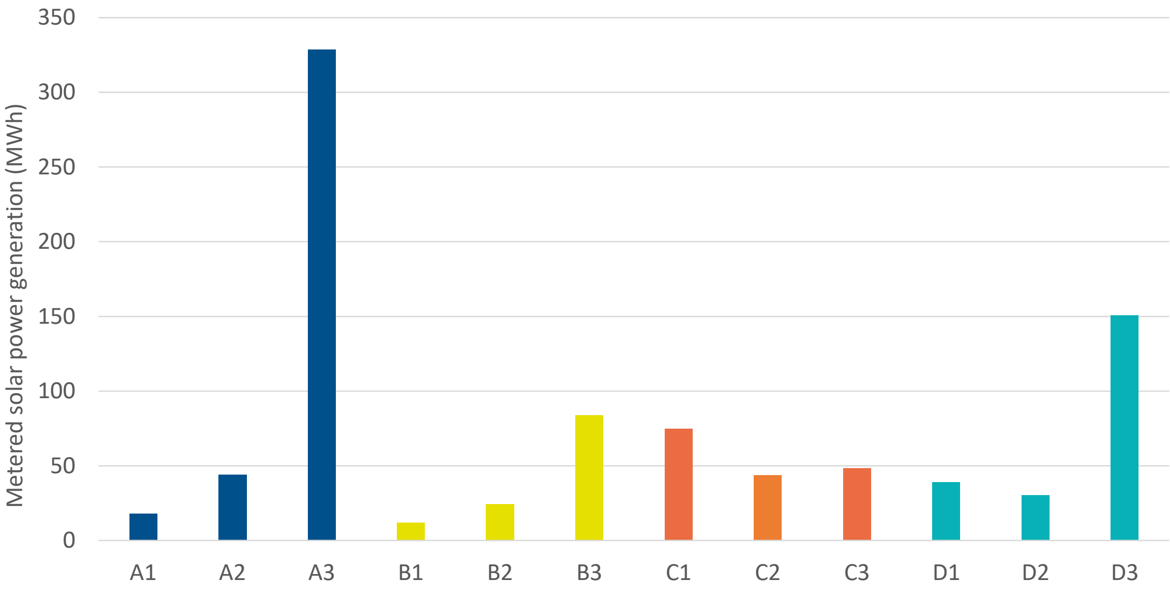


Figure 29 Curtailed solar power generation in all districts and variants

6.3 Indicator comparison

This section compares the results using the indicators of energy costs and self-sufficiency in order to evaluate how advantageous the district approach is compared to building optimization alone.

Another indicator for evaluating the district approach could be how useful the districts are to the overall system. This would involve evaluating the exchange of energy between the districts and the surrounding energy systems and how friendly to the grid and overall system the behavior of the identified energy systems is. This kind of investigation lay outside the scope of this short study due to resource limitations. However, it is recommended that this evaluation be carried out in a further study in order to generate further important insights into the interaction between districts and the system as a whole.

6.3.1 Specific energy costs

The most suitable indicator for evaluating the district energy systems is the resulting energy costs as presented above for the individual district variants. Figure 30 compares the specific energy costs in relation to the final energy demand for electricity and heat for each supply variant of the respective district. Comparing the 12 variants examined shows that within the district types A, B, C and D, the specific energy costs of the most expensive supply variant are between 45 percent and 82 percent higher than the costs of the cheapest variant. This cost difference is 45 percent in district A, 61 percent in district B, 79 percent in district C and 82 percent in district D. In districts A, C and D, figure 30 shows the trend that energy costs increase as the energy supply becomes more decentralized. This means that the energy costs are significantly higher for individual building optimization than for district optimization, making it an economically less attractive option from the perspective of the local investor. An economic assessment from the perspective of those investing in the general supply networks must be carried out in a follow-up study. The only exception to this trend is the rural district B, whose decentralized heat supply variant B2 is the cheapest.

In general, it should be noted with regard to the results that the LCOE for solar panels is around 5.8 cents/kWh across the different variants and around 8.7 cents/kWh for wind energy, including the surcharge for provision via a PPA (in each case without curtailment), and that these costs therefore also lie within the range identified in (Kost et al., 2021).

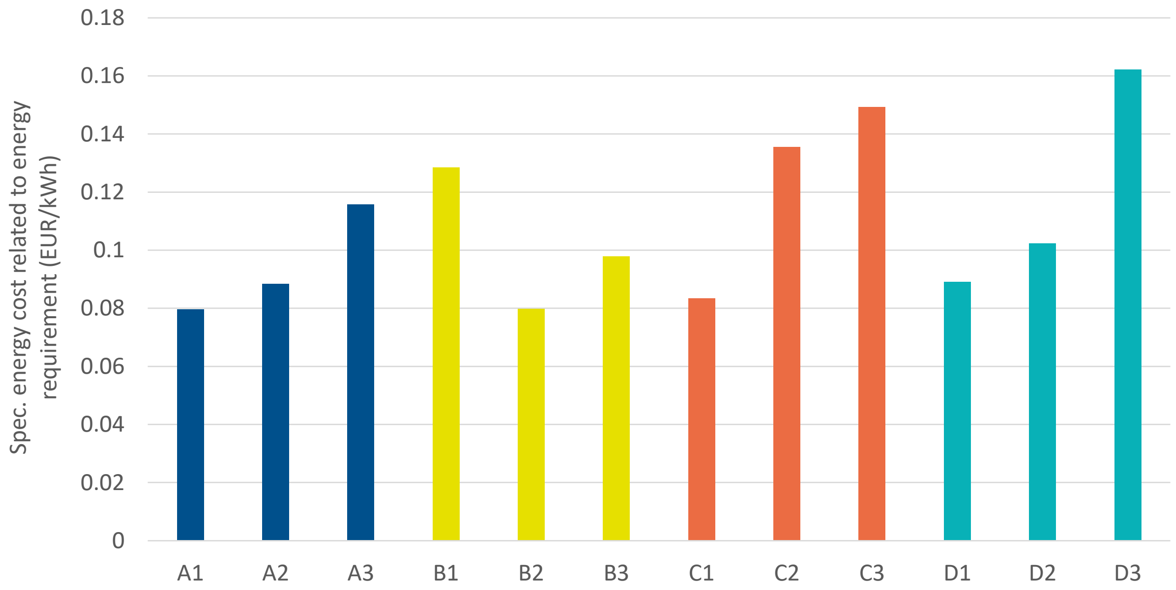


Figure 30 Comparison of specific energy costs for all districts and supply options

The reason for the higher specific energy costs of the full district solution (variant 1) in district B can be found when looking at the composition of the energy costs. Figure 31 reveals that the reason lies in the heating network costs, which are set at the same level in all districts and are based on the meters of pipe laid per building and the number of building connections. Demand for heat is significantly lower in district B than in the other districts, as district B is made up exclusively of single-family homes and duplexes (see figure 12), with the result that the specific heating costs are significantly higher and the costs of the heating network represent the majority of the costs of supply variant 1 in district B. Furthermore, figure 31 shows that imported electricity and fuels make up an increasing share of costs as the energy supply is increasingly decentralized.

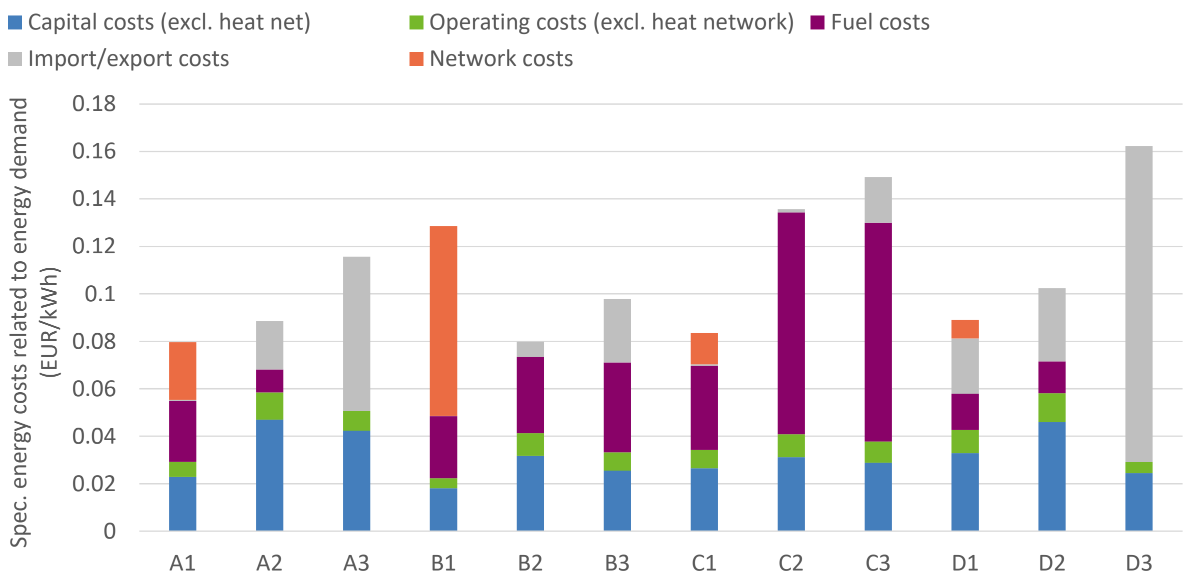


Figure 31 Comparison of specific energy costs for all districts and supply variants, broken down by cost type

Figure 32 shows the relative shares of the specific energy costs of the variants examined. It becomes apparent that operating costs always make up a small proportion of the energy costs, and that fuel and imported electricity costs together amount to more than 50 percent in the completely decentralized supply variants 3 across all districts. Comparing the variants in figure 32 also shows that the heating network costs (both capital and operating costs of the heating network) are responsible for more than 62 percent of the energy costs in district B, while heating network costs make up a smaller and smaller share of the respective energy costs as heat demand density increases (around 30 percent in district A, 16 percent in district C and just under 9 percent in district D).

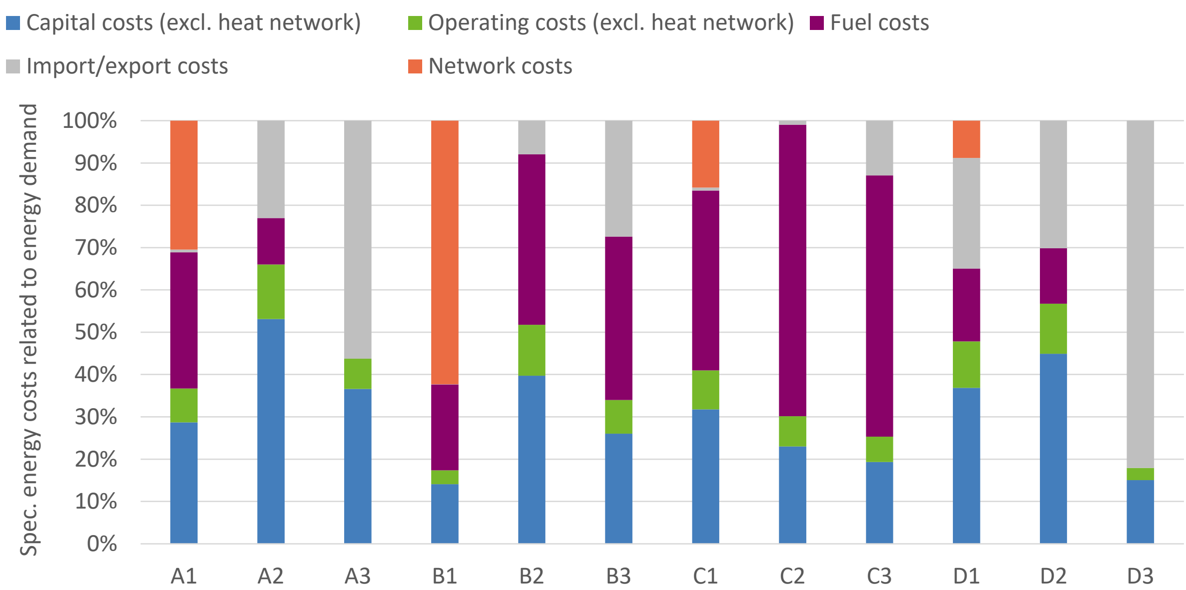


Figure 32 Comparison of specific energy costs for all districts and supply options, broken down by cost type, in relative terms

With regard to the classification of the results, it is important to note that the calculated energy costs represent the electricity production costs without taking grid fees, taxes and levies into account. This is irrelevant as long as the influence of this non-inclusion is the same for all variants. In fact, no grid fees, taxes or levies are incurred as long as the self-consumption of electricity and heat from rooftop solar panels or a CHP unit is involved.[5] For wind power purchased via a bilateral power purchase agreement (PPA), the purchase costs of 5 cents/kWh were taken into account. In contrast, the costs of electricity imports, which are subject to grid fees, taxes and levies, were set at 30 cents/kWh. This makes the consideration for the individual building supply realistic (variant 3).

The situation with the district-optimized solutions is more difficult to assess. In the heating sector (variant 1), shared use of heat sources is physically possible if a heating network is available. The production costs and infrastructure costs for the heating network are taken into account. However, the heat procurement costs are somewhat underestimated in that the heat is generated and distributed by heat suppliers that have operating costs and have to make a profit. However, the resulting surcharges can be assumed to be relatively small.

The assessment of the additional costs for a district-optimized electricity supply is more critical and uncertain. The electricity grid is already in place and was not taken into account in economic terms in the analysis. Within the current legal framework, optimizing the electricity supply at the district level through exchange between the buildings as envisaged in variants 1 and 2 is possible only if a customer system is set up, but that is only possible to a limited extent in terms of space and also entails costs for the creation and operation of the local electricity grid, metering point operation and billing, among other things. In the future, a district-optimized electricity supply could also be achieved by establishing renewable energy communities in accordance with the RED II EU directive. According to point (b) of Article 22(2) of the directive, Member States are required to ensure that "renewable energy communities are entitled to [...] share [...] renewable energy that is produced by the production units owned by that renewable energy community" (European Union, 2018). Germany has not yet transposed the directive into national law, so it is not yet possible to estimate the additional costs associated with this. However, they are likely to be much lower than the general grid fees, taxes and levies, as the matter involves only local exchange of electricity. In this respect, there is an urgent need for a balanced approach that focuses on the expansion of the central grid infrastructure from the macroeconomic standpoint while also providing incentives for local investors.

It should also be noted that in reality, energy generation plants are usually oversized for reasons of security of supply, which is not mapped in KomMod. The cost increase associated with this kind of oversizing of energy generation plants is greater in a decentralized energy supply structure (variant 3) than in centralized supply structures with a smaller number of plants. As a result, the costs of variant 3 shown in this study are slightly underestimated compared to variants 1 and 2.

The costs of variants 1, 2 and 3 are therefore all slightly too low, albeit for different reasons. However, the resulting uncertainties have such a small influence that they do not call into question the conclusion that there are clear cost advantages to a district approach.

[5] With the exception of the EEG surcharge, which will be abolished in mid-2022.

In summary, it can therefore be stated that district optimization on the electricity and heating side yields significant cost advantages compared to pure building optimization as long as there is sufficient heat demand density within the district. Where this is not the case, for example in rural areas with larger properties and a high proportion of single-family homes and duplexes, a decentralized heating solution combined with a district solution that has been optimized on the electricity side (variant 2) is preferable.

6.3.2 Degree of self-sufficiency

A district's degree of self-sufficiency describes the proportion to which the district covers its energy needs from its own energy sources. This is another important indicator for evaluating the districts and their supply options in this study. The electricity and heat generation from biogas CHPs are regarded as self-supply. Wind power plants whose electricity is purchased via a bilateral power purchase agreement (PPA) are also considered to be a local source of electricity.

Figure 33 shows the degree of self-sufficiency for all districts and variants in relation to the electrical energy supply. It should be noted here that the thermal self-sufficiency level of all the variants examined is 100 percent as long as no imported electricity is used to operate the heat pumps and heating rods. Due to this and the fact that heat exchange between the districts and the surrounding area was ruled out, the degree of electrical self-sufficiency as shown in figure 33 for the energy sources of solar, biofuel CHPs and wind is more meaningful in terms of evaluating the variants examined.

Comparing the aggregate self-sufficiency rates shown in figure 33 reveals that the district approach (variant 1) generally leads to higher self-sufficiency rates, which decrease the more decentralized the energy supply structure is. The degree of self-sufficiency decreases from 100 percent to 55 percent in district A, from 99 percent to 72 percent in district B, from 100 percent to 90 percent in district C and from 86 percent to 28 percent in district D in a comparison of centralized and decentralized supply. This is due to the decreasing possibility of integrating biofuel CHPs and wind energy as energy sources in a decentralized energy supply situation. In district C, CHP units are used for decentralized heat supply, which means that less electricity has to be imported. As a result, the overall degree of self-sufficiency decreases less from variant 1 to variant 3 in district C than in the other districts. It can also be stated that the district approach makes it possible to ensure complete (or almost complete) self-sufficiency in most cases (districts A, B and C). The exception here is district D, which has a comparatively high energy demand density and cannot use CHP units, so it has a self-sufficiency rate of 86 percent in variant 1.

An analysis of the composition of the self-sufficiency rates as shown in figure 33 from the energy sources of solar, CHP and wind shows different trends for the districts. For example, the degree of solar self-sufficiency in districts A and B increases from variant 1 to variant 3. This is accompanied by an increase in the solar potential utilization rate from variant 1 to variant 3 (see section 6.2.1) and at the same time an increase in the curtailment of solar electricity generation (see section 6.2.2). The reason for the rising trend in the solar self-sufficiency rate is the elimination of the comparatively favorable energy sources of CHP (from variant 1 to variant 2) and wind energy (from variant 2 to variant 3) as well as sufficient existing solar potential, with the result that as the energy supply structure is increasingly decentralized, solar panels account for a larger share of the energy generated locally.

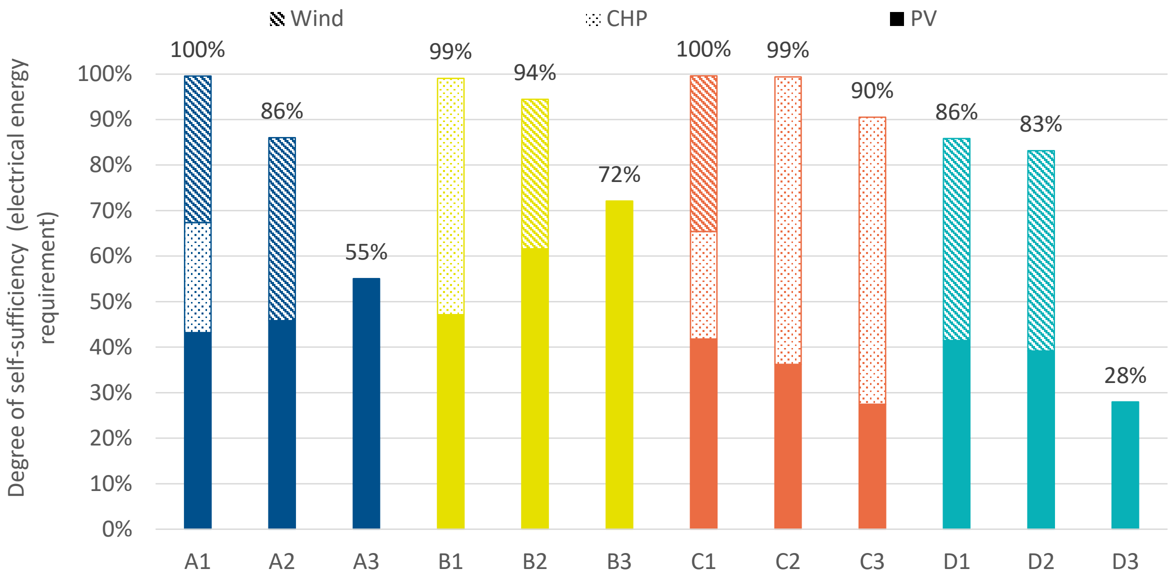


Figure 33 Degree of self-sufficiency in relation to the electrical energy demand for all districts and variants; wind turbines used via a PPA contract and biogas CHP plants are considered a local energy source and enable self-sufficiency (solid: solar, dotted: CHP, hatched: wind)

In districts C and D, the degree of district self-sufficiency due to the use of solar decreases with the increasing decentralization of the energy supply (from variant 1 to variant 3). There are several reasons for this trend. First, districts C and D have less homogeneous energy demand density compared to districts A and B (see figure 12) and therefore benefit more from the exchange of locally generated energy within the districts. With these district solutions and variant 2, the solar power potential of the buildings with lower energy demand density (residential buildings) can be used to supply the commercial buildings with higher energy demand density, which increases the total degree of self-sufficiency for that district that is due to solar power. Furthermore, the higher energy demand density of the commercial buildings in districts C and D means that solar panels can only contribute a small proportion to the degree of self-sufficiency of these buildings. This can also be illustrated by comparing the solar self-sufficiency rate for variant 3 across all districts in the context of their energy demand density. For example, rural residential district B3, which has high solar potential compared to energy demand, has the highest solar self-sufficiency rate, while the solar self-sufficiency rate drops to 55 percent with increasing energy demand density in the urban residential district A3 and reaches the lowest values, at 27 and 28 percent, respectively, in the urban mixed districts C3 and D3.

Taking all these analyses as a whole, it becomes clear that the district solution offers significant advantages in relation to districts' degree of self-sufficiency, especially if the districts have higher energy demand density and/or high, heterogeneously distributed energy demand density and different load profiles. In these cases, exchanging electricity between the buildings in the district offers great advantages and increases the districts' self-sufficiency levels.

6.4 Limitations of the KomMod results and evaluation of the sensitivity analyses

This brief study makes assumptions about the energy systems of the districts and how they interact with the superordinate grid levels and the region in general. In order to evaluate the district approach and compare it to a building-optimized energy system, the study assumes high electricity import prices and export costs and a lack of thermal energy exchange with the surrounding area, giving these additional weight to drive district self-sufficiency. The optimization calculations therefore minimize the sharing of energy with the surrounding area. For real districts, more-pronounced interaction with the surrounding energy system is also expected in the target year. However, the additional weighting of the above factors supports the investigations comparing the district approach and building optimization, which means that this somewhat artificial perspective is expedient in the context of this study. In addition, a more in-depth analysis of the interaction with the surroundings would go beyond the scope of this brief study.

In general, it should also be noted that the results of the optimization calculations represent idealized energy systems in the target year on the basis of optimization from the macroeconomic perspective. The transformation of the districts into these target systems is not explicitly mapped, with the result that aspects such as grid expansion and refurbishment costs are not considered. This is conducive to the aim of this study, which is to compare the district approach with individual building optimization, and any consideration of the different refurbishment costs would distract from this focus and exceed the scope of this brief study. It should also be noted that energy infrastructure and energy exchange within the energy system are mapped in simplified form in KomMod, and that the optimization does not address any direct infrastructure characteristics (e.g., optimal route length in the heating network).

Sensitivity analyses of the various parameters and boundary conditions (see appendix B) have shown that individual influencing variables can have a significant impact on the results calculated. However, the assumptions and data in this brief study are based on reliable sources and expedient assumptions, as shown. Furthermore, the technology portfolios of the various districts and supply variants studied provide a sufficiently nuanced picture to evaluate a wide variety of combinations of technologies and conditions. In addition, the input data and framework conditions defined are conducive to the focus of this study.

Based on these considerations, it can be concluded that the input data, boundary conditions and assumptions used do not significantly limit the informative value of this study with regard to the qualitative and quantitative assessment of the district approach compared to the optimization of individual buildings.

7 Evaluation of the overall legal conditions

In order to use districts as the basis for a regulatory framework, it is necessary to define the term "district" with sufficient precision. It is usually understood to mean a sub-area of a municipality or city that comprises several buildings at the least, and usually several city blocks. A district is a spatially coherent area whose geographic boundaries are sometimes not clearly defined and usually do not coincide with administrative boundaries. In this study, with its focus on energy supply, districts are defined by the fact that the district area is being newly developed and/or redeveloped as part of an urban planning development process. The district thus results from the inclusion of land areas and buildings in the development project, which is carried out by project developers. This definition is therefore temporarily limited to the development phase and may change again afterwards.

When looking at a district from an energy perspective, it is important to note that its area does not usually map neatly to the geographic units used by the energy supply structures and that the various energy supply sectors are also organized into different geographic units. In the electricity sector, for example, a supply unit or supply area is a distribution network area supplied by a local network transformer, while in the natural gas sector it is a low-pressure local distribution network supplied by a pressure reduction station and in the heating sector it is an independent local heating network or a sub-distribution network of a larger district heating network. The extent of the energy networks is an important criterion in defining areas for energy purposes, but it should also be borne in mind that although all buildings in a district may be connected to the electricity network, not all buildings need to be connected to existing gas and heating networks, meaning that these networks often do not cover the entire area. In addition to these physical area boundaries defined by the energy distribution networks, the area boundaries within which the operation of the energy systems is controlled are also important from an energy perspective. In an independent local heating network, the area of the heating network and its connected consumers is identical to the operating area. In the electricity grid, on the other hand, the grid operator does not control a single transformer and the grid section defined by it, but rather controls a larger number of grid sections via a grid control room. This makes it clear that achieving a particular energy objective for a given district, such as climate neutrality for that area, requires clear delineation of the area's boundaries on the one hand, but on the other hand must also be understood above all as a balance sheet objective that does not consider the district in isolation, but rather also takes into account how that district is integrated into and interacts with the surrounding energy systems.

Districts have not previously existed in energy law as a local level of organization and action between end consumers and energy suppliers and grid operators. The Energy Industry Act (EnWG) regulates the relationship between energy suppliers and household customers, for example, through the basic supply obligation. According to section 36(1) EnWG, energy supply companies are obligated to supply every household customer in grid areas in which they provide basic supply to household customers. According to section 36(2) EnWG, the energy supply company that supplies the most household customers in a general supply grid area is the basic supplier. This is redetermined every three years. The provision of energy networks is regulated by section 11(1) EnWG, which stipulates that the operators of energy supply networks are obligated to operate and maintain a secure, reliable and efficient energy supply network in a non-discriminatory manner and to optimize, reinforce and expand it in line with demand, insofar as this is economically reasonable (German Bundestag, 2021a).

The decentralized generation of renewable energy is regulated by the Renewable Energy Sources Act (EEG 2021). According to section 8(1) EEG 2021, grid operators must connect systems for the generation of electricity from renewable sources to their grid. Section 11(1) EEG 2021 stipulates that grid operators are also obligated to prioritize physically taking delivery of all electricity from renewable energy sources that is sold in the form of a market premium, a feed-in tariff, a tenant electricity surcharge or other direct marketing without delay (German Bundestag, 2021a).

The term "district" does not appear in the EnWG, and in the EEG occurs only in section 21(3), which stipulates that a claim to payment of the tenant electricity surcharge also exists if the end consumer to whom the tenant electricity is supplied is located in buildings in the same district as the building on which the solar power system with which the tenant electricity was generated is installed, provided that the supply is made without transmission through a grid (meaning a grid that is part of the general supply system).

7.1.1 Customer systems as district supply solutions within the present-day legal framework

In order to achieve climate neutrality in a district, an independent energy system (particularly an independent electricity grid) could be set up and operated in the district. However, energy law does not yet provide for such a solution. As a workaround, project developers are implementing what are known as "customer systems" (formerly "area grids") as defined by the EnWG in districts. According to section 3 no. 24a EnWG, customer installations are "energy installations for the supply of energy that (a) are located in a spatially contiguous area, (b) are connected to an energy supply grid or to a generation plant, (c) are insignificant in ensuring effective and undistorted competition in the supply of electricity and gas and (d) are made available to any person free of charge and without discrimination for the purpose of supplying the connected end customers by way of transmission, irrespective of the choice of energy supplier.

It should be noted at this point that a climate-neutral energy supply can be achieved only if all energy sectors (electricity, heating, cooling and mobility) are taken into account and linked together. Energy system analyses tend to focus on the electricity sector, as it is primarily organized uniformly at the national level, while the heating and cooling sectors are often implemented individually at the local level and legislation is therefore usually limited to setting a general framework. The energy supply for mobility is usually organized independently of local structures as long as fossil fuels are involved; in the future, it will increasingly fall within the electricity sector as electrification advances. This means that many energy industry regulations therefore relate to the electricity sector, so for the sake of simplicity the descriptions below also refer to the electricity sector. It is therefore necessary to translate these to the heating and cooling sector (including the gas infrastructure) in further considerations.

The left-hand side of figure 34 shows the usual electricity supply by energy suppliers under individual contracts with household customers, with an independent grid operator providing and operating the electricity grid. If, on the other hand, a customer system is installed in the district, as shown in the diagram on the right, a local player operates the electricity grid in the district or parts of the district and can also sell electricity from its own power generation plants to households. The individual household must also be able to choose a different electricity supplier without discrimination. The grid operator ensures that the customer system is connected at the transfer point. The operator of the customer system supplies the connected end consumers with locally generated power and, if necessary, imported electricity, which it obtains via an electricity supply contract with an energy supplier.

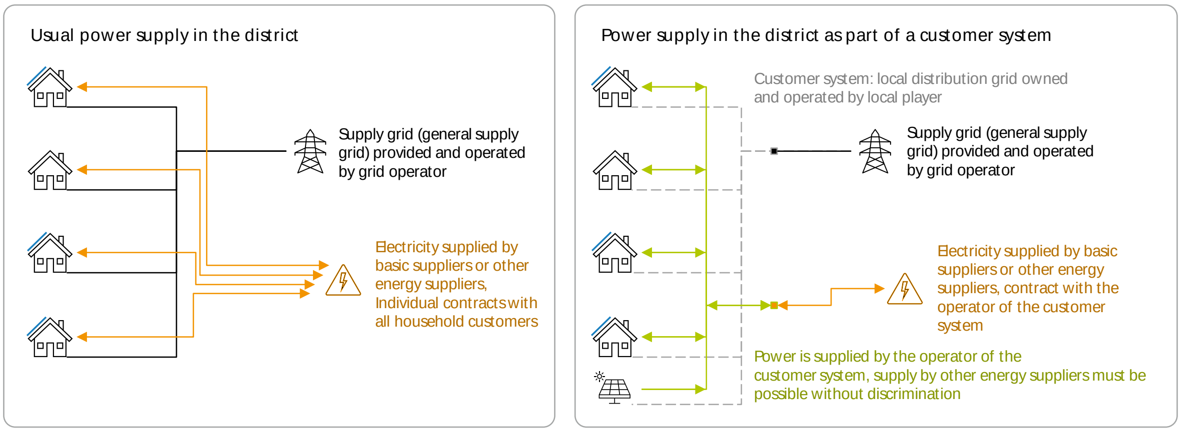


Figure 34 Electricity supply models under the current legal framework: usual supply (left) and supply as part of a customer system in accordance with section 3 no. 24a EnWG (right)

From the perspective of developers and users of district concepts, classification as a customer system has the advantage that neither grid fees nor other grid usage-related levies and charges are incurred for the electricity generated within the customer system and supplied to consumers there. This is currently used as an economic advantage that ensures the competitiveness of "local electricity" in terms of sales, but it also raises questions from the perspective of the overall system (final consolidation). Progress in this respect urgently requires, as noted above, a balanced approach that focuses on the expansion of the central grid infrastructure in macroeconomic terms while also providing incentives for local investors. In addition, energy industry law provides for certain administrative simplifications for electricity supplied within customer installations (see, for example, section 5 EnWG). Above all, however, a customer system is not part of the public electricity grid — and is therefore exempt from the complex and extensive energy law regulations that apply to grid operation and from the associated obligations (von Bredow Valentin Herz Rechtsanwälte, 2018).

However, some aspects of the use of customer systems in districts are controversial, such as the criterion of the spatially contiguous area and the relevance to competition, on which the Federal Court of Justice (FCJ) issued a ruling on December 11, 2019. The criterion of a spatially contiguous area is considered to be of secondary importance; according to the court, an area is also considered to be spatially contiguous, in particular, if the customer system extends over multiple properties and these properties are almost exclusively supplied via the customer system. The ruling holds that this is particularly the case if properties are adjacent to each other and are not scattered and that no obstacle is posed if an area delineated in this way includes streets, similar public spaces or includes isolated, insignificant other properties that are not supplied via the customer system (Richter and Herms, 2020).

According to the court's ruling, the key factors in assessing relevance to competition are not only the number of end consumers connected, but also the quantity of energy transmitted and the geographic extent of the energy system. In this view, and subject to the overall assessment to be carried out by the court determining the facts of each case, classification as insignificant in terms of competition is generally ruled out if several hundred end consumers are connected, the energy system supplies an area of significantly more than 10,000 m^2, the annual amount of energy transmitted is expected to significantly exceed 1,000 MWh and multiple buildings are connected. If, on the other hand, the energy system falls short of the stated values for several of these points, it should generally be considered a customer system that is insignificant to ensuring effective and undistorted competition in the supply of electricity and gas (Hoffmann Liebs Partnerschaft von Rechtsanwälten mbB, 2020).

In summary, it can be stated that, according to the current legal situation, customer systems can only enter into consideration for small districts with fewer than 100 end consumers and under certain restrictive conditions, with the legal framework still being open to interpretation in some cases. This means that customer systems are probably only a solution for implementing independent local supply for a small proportion of districts unless and until there are changes in the legal framework.

7.1.2 Local energy communities: alternative business model for districts

Setting up a district supply separate from the general supply grid with an independently operated electricity grid as a customer facility in accordance with the Energy Industry Act (EnWG) is one way to optimize the electricity supply within the district and achieve the highest possible proportion of local use of renewable energy, but it is not the only way. It is also possible not only for electricity to be procured and supplied bilaterally between the end consumers and an energy supplier — usually one that operates beyond the individual region — but also for the local exchange of electricity between the end consumers in the district to be enabled, all without changing the general supply grid. Since the electricity grid remains unchanged in this scenario, there may be only slight change in the physical flow of electricity. From an accounting perspective, however, deliveries of electricity volumes between and among local players will trigger changes in how the energy system operates, stakeholders' consumption behavior, and even the structure of the local energy system, by stimulating investments in elements such as solar panels, battery storage, heat pumps and/or electric vehicles. However, the prerequisite for this is that local exchange of electricity between the players must be readily possible without a lot of time, effort, and expense and must bring significant cost benefits in terms of grid fees, taxes and levies.

The concept of privileged electricity exchange between end consumers has been developed at the European level in recent years under the term "energy communities." The EU Renewable Energy Directive (RED II) was adopted as part of the EU's 2018 Clean Energy Package. Article 22 of the directive provides for the introduction of "renewable energy communities" (European Parliament and Council, 2018). In addition, the EU Common Rules for the Internal Market for Electricity Directive (IEMD) was adopted in 2019. Article 16 of this directive requires Member States to adopt a regulatory framework for "citizen energy communities" (European Parliament and Council, 2019). The aim of both forms of energy communities is to enable and facilitate the generation and exchange of energy between local producers and consumers.

Article 22(2) of RED II requires Member States to ensure that final customers, and particularly households, are entitled to participate in a renewable energy community, and that these communities are entitled to (a) produce, consume, store and sell renewable energy; and (b) share renewable energy produced by their own production units within the renewable energy community. Article 22(4) of RED II requires Member States to provide an enabling framework to promote and facilitate the development of renewable energy communities. This framework must ensure, among other things, that the relevant distribution system operator cooperates with renewable energy communities to facilitate energy transfers within renewable energy communities, that renewable energy communities contribute to the overall system costs in an appropriate and balanced manner, and that participation in renewable energy communities is open to all consumers, including those living in low-income or vulnerable households.

The IEMD consists primarily of optional provisions with regard to citizen energy communities. For example, Member States are permitted to stipulate that these communities are entitled to arrange within the community the sharing of electricity that is produced by the production units owned by the community (point (e) of Article 16(3) IEMD). Member States may also may decide to grant citizen energy communities the right to manage distribution networks in their area of operation (Article 16(4) IEMD). In general, citizen energy communities may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to their members or shareholders (point (c) of Article 2(11) IEMD).

A citizen energy community under the IEMD is a legal entity whose members may be natural persons, local authorities, including municipalities, or small enterprises (point (a) of Article 2(11) IEMD). Member States may stipulate in the enabling framework for citizen energy communities that these communities are open to cross-border participation (point (a) of Article 16(2) IEMD). This means that households and other local stakeholders can join together in citizen energy communities, but these citizen energy communities can also extend far beyond a district or city and possibly even work across national borders.

A renewable energy community is a legal entity whose shareholders or members are natural persons, SMEs, or local authorities, including municipalities, located in the proximity of the renewable energy projects that are owned and developed by that legal entity (Article 2(16) RED II). There is no precise definition of what project proximity means, but since it is also possible to operate wind and biofuel plants, among other options, it can be assumed that renewable energy communities will operate regionally and be active beyond city limits. On this point, it is important to distinguish between the spatial extent of the locations of the members (consumers) and the locations of the community's renewable energy installations.

Once the legal basis has been established, both citizen energy communities and renewable energy communities can be founded within a given district to optimize that district's energy supply. However, as households and end consumers must actively join a legal entity and this membership is of course voluntary, it can be assumed that not all stakeholders in a district will become members. In addition, the energy community can also accept consumers outside the district and operate renewable energy systems outside the district. This means that the energy system operated by the energy community can be largely congruent with the district energy system, but this is not required, and it can also deviate greatly from it.

The structure of a local energy community is shown schematically in figure 35. The physical electricity supply is provided entirely via the general supply grid. For accounting purposes, the exchange of electricity volumes takes place between the stakeholders involved. By way of example, the figure shows that some of the end consumers are not part of the energy community and the energy community operates solar panel arrays and wind turbines outside the district.

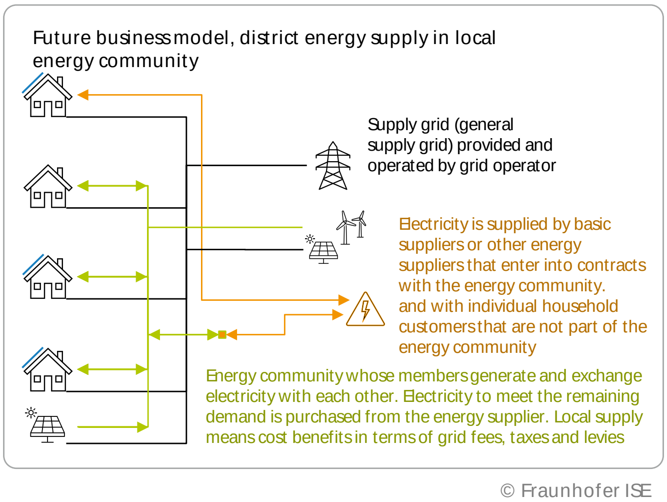


Figure 35 Future business model for electricity supply in the district with the introduction of local energy communities

It is not yet possible to assess how attractive the establishment of local energy communities in districts actually is, as no national legal framework has yet been created for this. According to EU law, the IEMD should have been transposed into national law by December 31, 2020, and RED II by June 30, 2021, but this has not yet occurred in Germany. The same is true in a number of other EU countries.

7.3 Summary

The goal of climate neutrality for a district makes sense, as the energy transition can only succeed if district developers also pursue this goal in their planning. However, local energy systems are not currently being optimized at the district level, partly because the current regulatory framework does not provide for structures and players that could pursue and implement this. The players in the energy industry usually optimize their energy system in larger geographic units. In contrast, the current legal framework does not allow local players (such as housing associations and end consumers) themselves to set up supply structures at the district level that readily enable the exchange of energy between the players in the district. The only possible solution is customer systems in accordance with the Energy Industry Act (EnWG), although they are probably only an option for a small number of districts due to the tightly defined conditions.

At the same time, prioritizing the generation of renewable energy in the immediate vicinity of consumers and tapping into synergies through local sector coupling, storage and local energy management are increasingly being recognized as important components of a climate-neutral energy supply and discussed under the term “local supply.” For example, the authors of the food-for-thought paper titled “Unleashing the local potential of the energy transition” (Original title: “*Vor-Ort-Potenziale der Energiewende entfesseln*”) point out that, in addition to the international and national levels, a third level characterized by local solutions will be added to the future energy system. The paper points out that the technologies for local coupling of sectors, such as solar arrays, heat pumps, wall boxes, storage systems, local energy management systems and digital control and metering infrastructure are available, and that local supply has long been technically possible and affordable as well. A local energy supply that serves the system and is an important element of the future energy system has largely become accepted as common sense. However, there is a lack of viable business models for efficiently linking these technologies across sectors to create integrated local solutions (Henning et al., 2021).

This makes it clear that there is an urgent need to further refine the regulatory framework in order to enable the optimization of energy systems at the district level as an important contribution to local supply arrangements. Two paths, which can be pursued in parallel or alternatively, are conceivable here. **The first path consists of further refining the regulation of customer systems** so that they can be applied to typical district structures in terms of size, number of connected end consumers, energy volumes and number of buildings. In this case, independent local grids would increasingly be created at the district level, which is why the districts’ influence on the upstream electricity system must also be taken into account and the districts must be required to contribute favorably to the overall system, with assessment of the degree to which this is the case. Rules for fair financing of the system costs by the operators of the customer systems and other entities must also be developed. **The second path consists of developing a regulatory framework for the implementation of local energy communities**, with this framework being geared rigorously toward the establishment at the district level of energy communities that implement and operate an energy system locally that is characterized by a high level of self-sufficiency and a high degree of utility for the upstream energy system. To this end, RED II must be transposed into German law as swiftly as possible. When creating the regulatory framework for renewable energy communities, however, care must be taken to ensure that sufficient incentives are created for the establishment of local communities that strive to produce as large a portion of their energy as possible locally in the district while also operating in a way that serves the overall system by providing flexibility for the upstream energy system. It must be ensured that optimization is geared not only toward the electricity system, but rather toward the overall energy system and the coupling of the electricity, heating, cooling and mobility sectors.

8 Conclusion

This study used optimization calculations for district energy systems to analyze whether the district approach has quantitative advantages for supplying energy to districts as compared to supply structures optimized on a decentralized basis at the building level. The studies were carried out for the target year 2045 using four different types of districts in Germany as examples, each with three different energy supply structures, all of them characterized by a climate-neutral energy supply. At this point, reference should be made to the limitations of the study results, which are presented in section 6.4.

The study results show that the district approach with district-optimized electricity and central heat supply infrastructure is advantageous compared to decentralized, building-optimized energy supply concepts. The district approach is particularly advantageous in terms of specific energy costs and the degree of self-sufficiency, as the existing potential for generating electricity from renewable sources can be better utilized and regional wind energy potential can be included in the energy supply. In addition, other energy sources such as biofuel combined heat and power (CHP) plants and waste heat potential can be better tapped and integrated within the central heat supply. In this way, the district approach has significantly lower specific energy costs compared to energy supply structures organized on a decentralized basis. The only exception to this is rural districts, which do not have sufficiently high heat demand density to operate a heating network economically, with the result that a decentralized heat supply with a central or district-optimized power supply, including electricity exchange between the buildings, is the most cost-effective solution.

One important advantage of the district approach is the assumed no-cost exchange of electricity between buildings in the district, which enables shared use of solar panels and other electricity generation potential in the district as a whole. Especially in districts with higher energy demand density and thus a lower possible degree of self-sufficiency of the individual buildings, exchanging electricity among buildings can offer considerable advantages in reducing energy costs and increasing the entire district's degree of self-sufficiency. This applies in particular if the buildings in a district have heterogeneously distributed energy demand densities and/or different load profiles (e.g., in mixed districts with residential and commercial use). Based on the linking of the electricity and heat sectors of the target energy systems by means of heat pumps and heating rods as contemplated in this study, exchanging electricity between the buildings also has a positive effect on the decentralized supply of heat to the buildings. Thus, all of the districts and variants examined have a completely climate-neutral heat supply — which, depending on its characteristics, has a different proportion of power-to-heat in the heat supply — and reflect a heat transition completed by 2045.

List of illustrations

List of tables

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Abbreviations

a	Year
CHP	Combined heat and power plant
COP	Coefficient of performance
Dec.	Decentralized
SFH	Single-family home
el.	Electric
TCS	Trade, commerce and services
h	Hour
ISE	Fraunhofer Institute for Solar Energy Systems ISE
kg	Kilogram
km	Kilometer
km²	Square kilometer
km/(car·a)	Kilometer per passenger car and year
kW	Kilowatt
kWh	Kilowatt-hour
kWh/a	Kilowatt-hours per year
kWh/(m²·a)	Kilowatt-hours per square meter and year
CHPG	Combined heat and power generation
l	Liter
m	Meter
m²	Square meter
MFH	Multi-family house (building)
m/s	Meters per second
MW	Megawatt
MWh	Megawatt-hour
MWh/a	Megawatt-hours per year
PPA	Power purchase agreement (bilateral)
PV	Photovoltaic

RED	Renewable Energy Directive (EU directive on the promotion of the use of energy from renewable sources)
Spec.	Specific
Std.	Standard variant
ST	Solar thermal energy
th.	Thermal
TRY	Test reference year
DHW	Domestic hot water
FT	Flow temperature
HP	Heat pump
TFH	Two-family house (building; also “duplex”)

Appendix A: Curtailed energy quantities

Figure 36 shows the quantities of all curtailed energy generation. As discussed above, these energy volumes could be used elsewhere (e.g., to produce hydrogen).

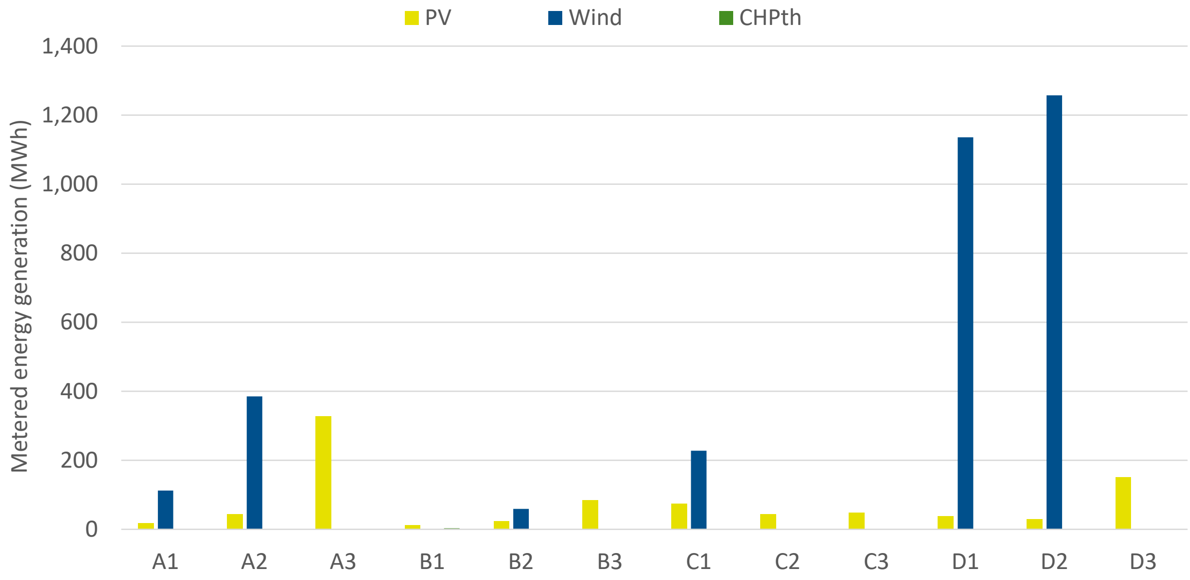

Figure 36 Annual curtailed electricity generation from solar panels and wind and curtailed thermal energy generation from CHP units in all variants examined

Appendix B: Sensitivity analyses

The results, analyses and conclusions presented in this study depend on the scenarios examined and the assumptions made. This applies in particular to the input data selected. In order to evaluate the robustness of the results presented and the generalizability of the statements made, various sensitivity analyses are carried out and briefly presented here. These sensitivity analyses are carried out on the basis of district A variant 1, district C and district D.

Waste heat potential

In the district solutions examined for variant 1, the available waste heat potential was limited to 50 percent of the respective annual heat demand energy quantity and the maximum heat demand output in districts C and D. In a sensitivity analysis, these restrictions were lifted and it was only stipulated that the waste heat output must not exceed the maximum heat demand output. The removal of the restrictions in the optimization calculations has no significant impact on the energy system in C1.

In district D, the integration of greater waste heat potential results in significant changes in the energy system for variant 1, as shown in figure 37 for heat generation. For example, the increased use of waste heat potential reduces the installed capacity of the central heat pump connected to the heating network from 510 to 92 kW (see “Standard” compared to “Unlimited waste heat”). The installed capacity and operation of the decentralized booster heat pumps are not affected by the removal of the limit on waste heat potential, as the decentralized provision of domestic hot water does not change. The higher amount of waste heat in the energy supply is accompanied by a reduction in the full load hours of waste heat utilization (from 2,163 h to 1,951 h). Furthermore, less wind energy is used and slightly more electricity is imported in order to use the electricity-based heat supply more flexibly.

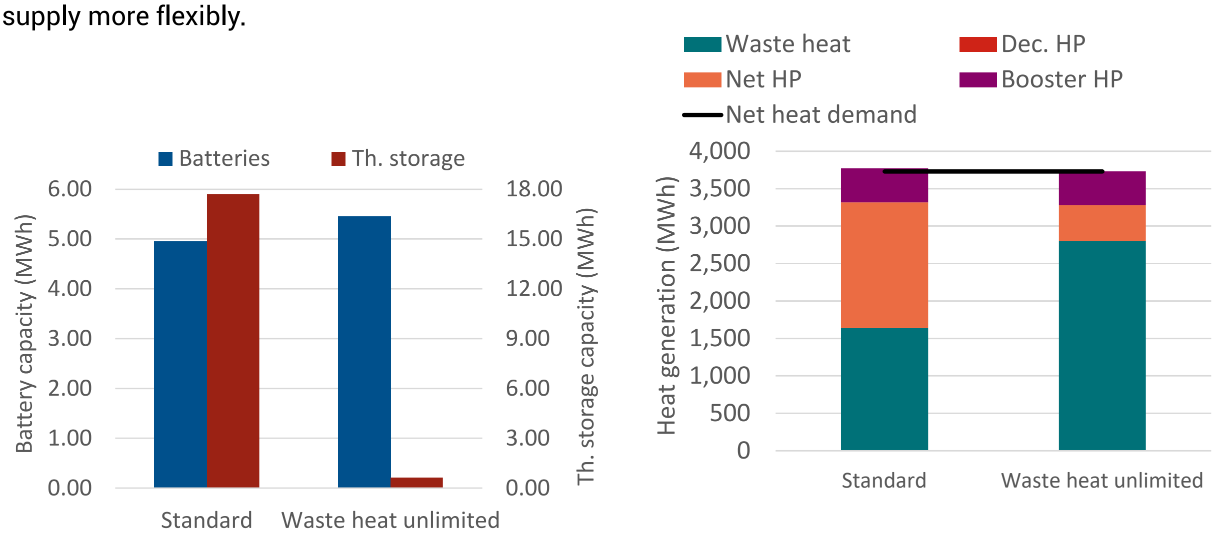

Figure 37 Annual heat generation (left) and installed storage capacity (right) in district D variant 1 with waste heat potential limited to 50 percent of the heat demand and unlimited waste heat potential

Another change in the composition of the energy system is the significant reduction in thermal storage capacity, as illustrated in figure 37. As a result of the more flexible use of the different heat supply technologies, demand for thermal storage falls sharply, while the installed battery capacity increases slightly. Performing the optimization calculations without limiting the waste heat potential to 50 percent leads to lower overall costs compared to the calculations with the 50 percent limitation. This cost reduction corresponds to a small savings of EUR 0.0015/kWh in terms of energy consumption. The district's degree of self-sufficiency also rises, but only by a negligible amount.

Based on the results presented and analyses of how restricting waste heat potential affects the energy systems in districts C and D, it is concluded that the restriction of potential as described does not lead to any significant distortion of the results and evaluations already presented and discussed for districts C and D.

Storage capacity

The thermal storage volumes obtained from the optimization calculations (see section 6) exceed in some cases the storage volumes that are customarily planned for decentralized storage systems today. The thermal storage capacity determined for district D is comparatively higher than the storage volumes for the other districts. A sensitivity analysis is therefore carried out below for the thermal storage capacity in district D and compared with the standard variant (Std.) already discussed. The central storage for variant 1 is limited to 360 m³, and two different considerations are performed, one with decentralized storage of 600 l per building and the other with 2,000 l per building. For decentralized heat supply variants 2 and 3, storage volume limits of 600 l and 2,000 l per building are also applied in the individual sensitivity calculations. Figure 38 shows the installed capacity to cover the demand for heat. While the limitation of storage in variant 1 has only a marginal impact on the energy system, the installed heat pump capacity in the decentralized heat supply variants increases first to a moderate degree (2,000 l) and then sharply (600 l). Analysis of the full load hours shows that when storage volumes are severely limited, the higher installed heat pump capacity is used to cover peak demand and the heat pumps are operated more unevenly. This higher installed generation capacity is accompanied by higher energy costs, as thermal storage capacity is cheaper than additional heat pump capacity. While the impact on the heat capacity installed on a decentralized basis is significant when decentralized storage volumes are severely restricted, there is little impact on the district's electricity supply.

The sensitivity analysis shows that larger storage volumes lead to more favorable energy systems with a more even heat supply. Even today, buffer storage systems are sometimes installed with somewhat larger dimensions in order to take account of the increase in the flexibility of the energy supply. The sensitivity analysis did not show any significant influence on the trends identified or the statements on the results for district D. It is therefore concluded that the evaluations and comparisons of the district approach carried out within this brief study are not distorted by the unlimited thermal storage volumes used in the optimization calculations.

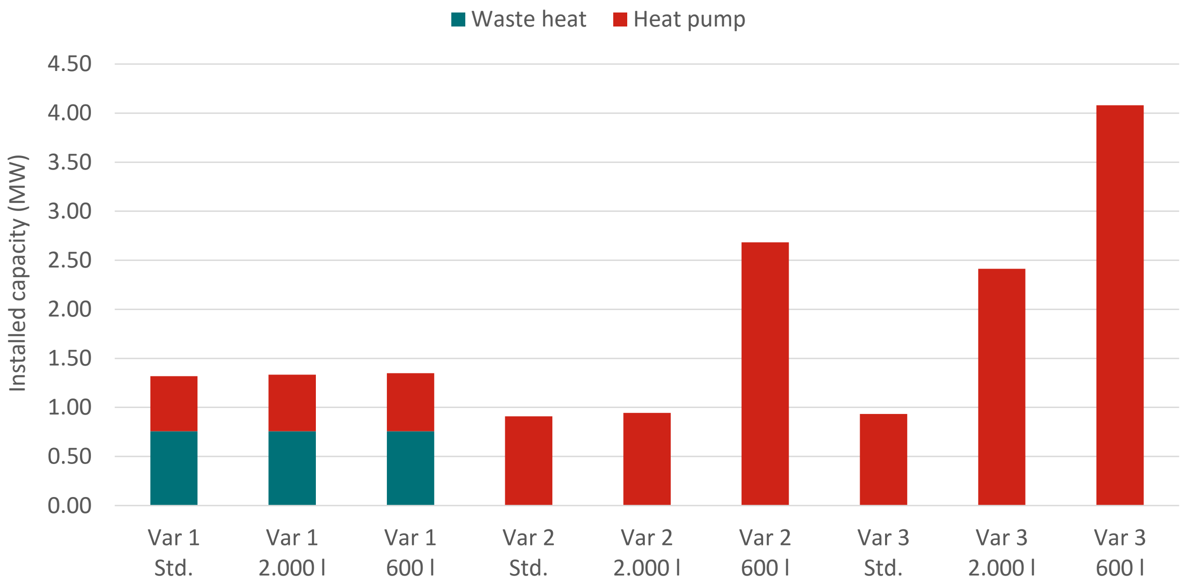

Figure 38 Influence of maximum thermal storage capacity on installed heat generation capacity in district D

Biogas price

The influence of biogas prices on the energy system is examined with an eye to the effects of the costs of biofuels, taking district A variant 1 as an example. As shown in figure 39 for the energy supply with biogas prices between EUR 0.04 and 0.16/kWh, the price of biogas influences the share of the energy supply made up by CHP units. Thus, the installed capacity and the amount of energy supplied by the CHP units decrease with increasing fuel prices in favor of solar and wind energy, until electricity imports replace the electricity generation of the CHP units at a price of EUR 0.16/kWh. Due to their lower number of full load hours, the increase in installed capacity for solar and wind is sharper than the rise in their respective share of electricity demand coverage. In the heat supply sector, it is also apparent that heat pumps make up a larger share of the heat supply as the price of biogas rises. Since — as shown in figure 32 — fuel costs account for around a third of the energy costs in district A1, the energy costs of the overall system fall with more favorable biogas prices. Installed storage capacity increases significantly at biogas prices of EUR 0.08/kWh or more in order to compensate for the increasing share of fluctuating electricity generation from renewable sources. This trend can also be seen to a comparatively small extent in battery capacity, but due to sector coupling and increasing heat generation from heat pumps, thermal storage capacity increases significantly with increasing electricity generation from solar and wind energy.

The significant influence of biogas prices on the energy system in district A1 as discussed above is expected and understandable. Depending on how large a share of the total energy costs falls to fuel costs (see figure 32), similar effects of fuel costs on energy systems can be expected for the other variants examined. Determining the price of biogas is therefore relevant to the results of this study. The fuel prices set for 2045 (see section 5.7) are based on reliable sources. It is assumed that the results presented for the variants examined are reliable with regard to comparing the district approach with building optimization.

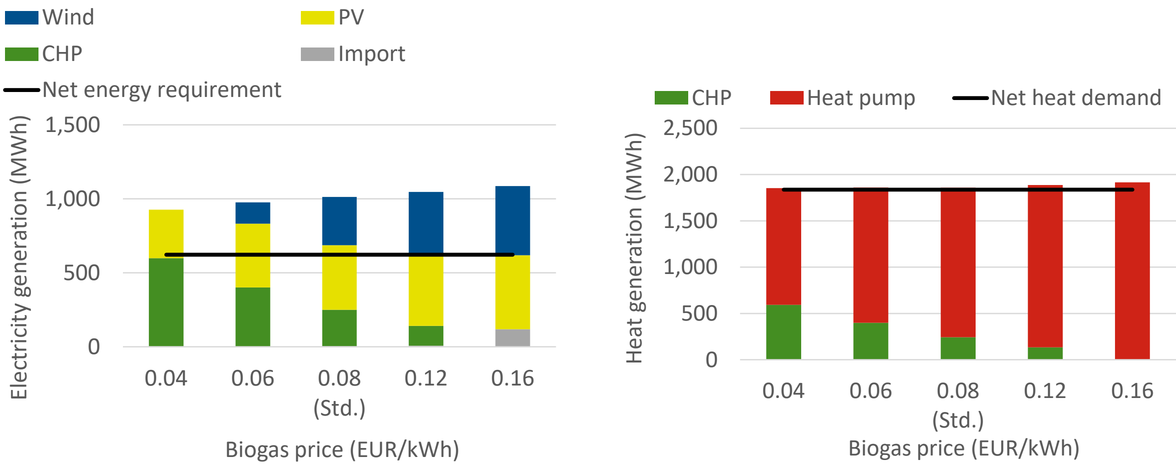

Figure 39 Influence of biogas prices on annual supply of electricity (left) and heat (right) in district A variant 1

Export electricity price

In times of excess electricity production from fluctuating renewable energy sources such as solar and wind, the surplus electricity could be exported. As the results already presented show, curtailment of solar and wind power production is preferred to exporting electricity, which is costly. Variant 1 in district A is used to examine the influence of electricity export costs on the energy system. Figure 40 shows that changing electricity export costs have no significant influence on the energy system as long as no revenues are generated through electricity exports. Even where electricity exports are free of charge, curtailment — which is currently economically equivalent from the perspective of the energy system — is predominantly used, and electricity exports are only marginal. From an optimization perspective, the two methods should be viewed as equal, leading to the same cost minimum. If electricity export costs are greater than 0, no electricity is exported.

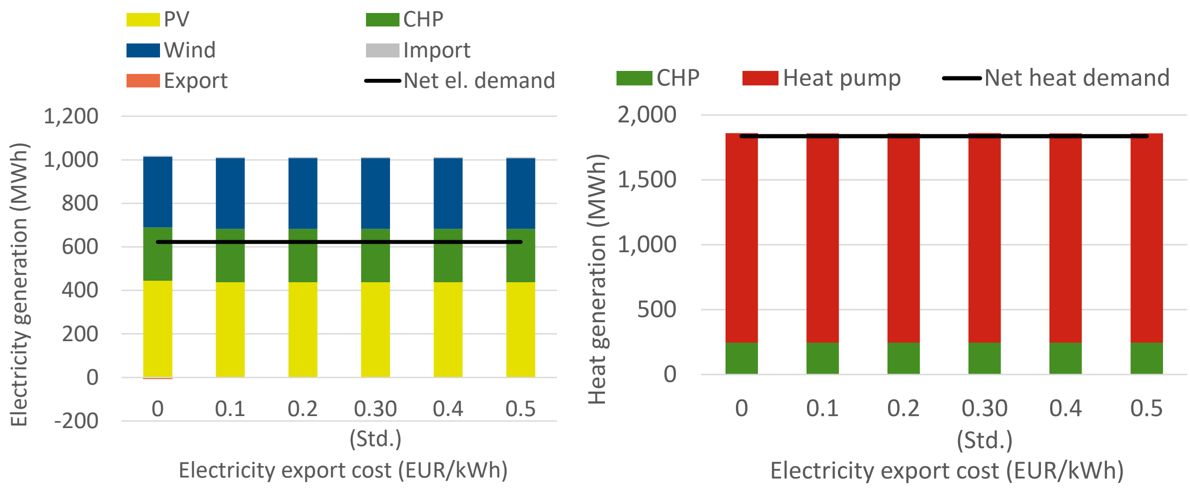

Figure 40 Influence of electricity export costs on annual supply of electricity (left) and heat (right) in district A variant 1

The analysis shows that changing electricity export costs do not have a significant impact on the energy system, as curtailment is the more cost-optimal alternative to exporting electricity, which is associated with costs. As shown in section 5.7 above, curtailment of energy generation is equivalent to exporting energy free of revenue and costs. A different picture would emerge in the case of revenues from electricity exports. Within this study, it is assumed that electricity exports from the districts cannot generate any revenues, as the electricity surpluses to be exported come from renewable energy production in the district and it is expected that the surrounding energy system will have an electricity surplus at the same times in the target year, 2045.

Import electricity price

The influence of the import electricity price on the energy supply of district A1 is examined below (see figure 41). It is apparent that a change in the import electricity price has only a marginal impact on the energy system as long as the import costs are at least EUR 0.20/kWh. With a lower import electricity price of EUR 0.10/kWh, the amount of imported electricity increases significantly, and wind energy and CHPs are forced out of the system. This is due to the higher LCOE of wind power compared to import costs, as wind power gives rise to additional PPA costs and is curtailed at times, and to the LCOE of CHP units in the respective calculations. A similar trend can be observed with regard to storage capacity, with the result that the only significant difference from the standard variant, at EUR 0.30/kWh, arises in the case of electricity import costs of EUR 0.10/kWh. The increased imports of electricity lead to significantly lower battery capacity and slightly higher thermal storage capacity. The lower proportion of the electricity supply that comes from renewable sources in the case of low electricity import costs of EUR 0.10/kWh leads to a considerable reduction in the district's level of self-sufficiency, as electricity imports play a significant role.

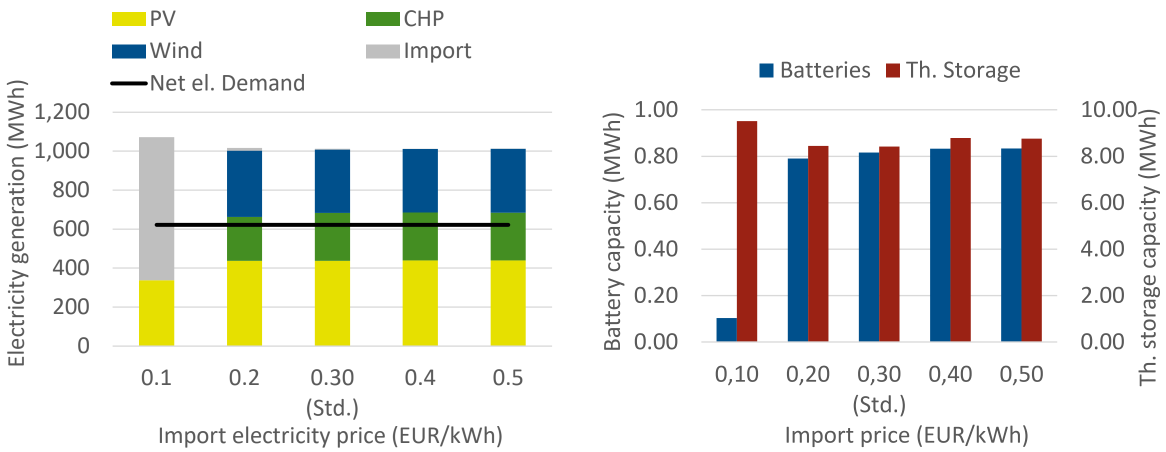

Figure 41 Influence of import electricity prices on annual electricity generation (left) and installed storage capacity (right) in district A variant 1

It can be stated that the import electricity price has no significant influence on the energy system of district A1 as long as the electricity generation costs of the technologies assigned to the district are lower than the import electricity costs. Once imported electricity becomes available as a low-cost alternative (EUR 0.10/kWh), it is used extensively, displacing more expensive technologies from the energy mix. Since in the standard analyses in this brief study, the import electricity price is always higher than the electricity generation costs of renewable energy sources, district self-sufficiency, which is the focus of this study, is preferred. As shown above, focusing on district self-sufficiency makes it easier to compare the district approach and building optimization. Consequently, the electricity import price applied is sensibly chosen with regard to the objectives of this brief study.

Combined heat and power generation

Supply variant 1 for district A is used to examine the influence of the biogas potential and thus the existence of the CHP units on the results. Figure 42 shows the energy supply for the district in the standard case and without CHP. In the absence of CHP, solar and wind energy occupy higher shares of the electricity supply to compensate for the lack of CHP power generation. However, the higher installed solar and wind power capacity is not sufficient, so additional electricity is imported. This significantly reduces the district's level of self-sufficiency and increases energy costs. Due to the provision of heat using heat pumps and the increased amount of fluctuating electricity generation from renewable sources, storage capacity increases, with thermal storage having significantly higher capacity, as storing the heat generated from renewable electricity using heat pumps is cheaper than storing electricity in batteries. As this thermal storage takes place over longer periods of time, this results in higher storage losses, which are reflected in the difference between net heat demand and heat generation in figure 42.

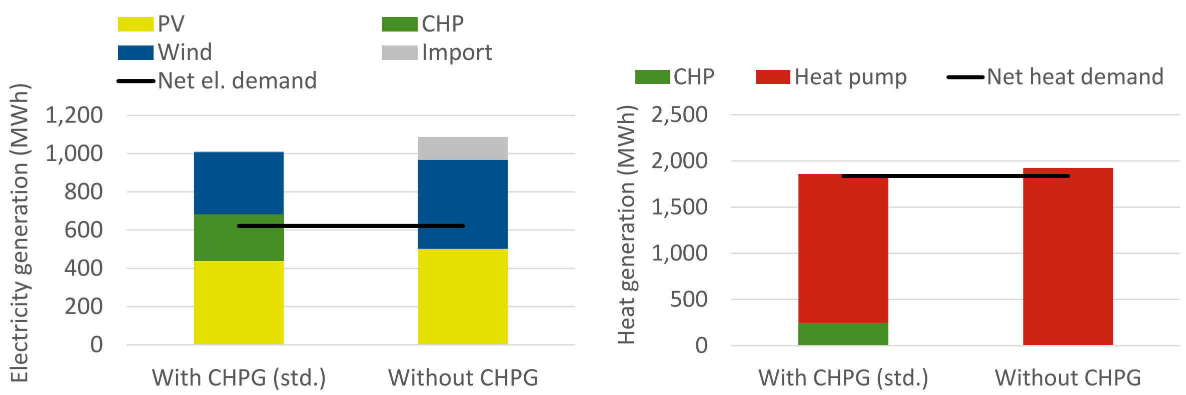

Figure 42 Influence of the existence of heat/power cogeneration on annual supply of electricity (left) and heat (right) in district A variant 1

The lack of heat/power cogeneration leads to a situation similar to supply variant 2 in district A, although in contrast to variant 2, the heating network still exists. In principle, the existence of biogas potential is of significant importance for district A, as the energy sources in supply variant 1 are otherwise modest.

In principle, it can be concluded from these observations that the definition of the technology portfolio of the supply variants has a significant influence on the results presented in this study. On the basis of the differentiated technology portfolio selected for the various districts and their supply variants, it is concluded that this study considers all relevant technologies, with the result that fundamental statements can be made about the district approach and its qualitative and quantitative evaluation for the variants shown.

Wind energy

Much like in the investigation of biogas potential, the influence of wind energy potential on the energy supply of district A1 is examined below. Figure 43 shows the generation of electricity and heat. It is clear that the loss of wind energy potential is compensated for by increased solar potential utilization and the installation of larger CHP units with significantly higher energy generation. As a result, the role of heat pumps in the district's heat supply is reduced. Although the full load hours of the CHP units are increased due to the lack of wind energy potential, the energy costs of the district energy system increase, as wind energy is missing as a cheaper source of electricity.

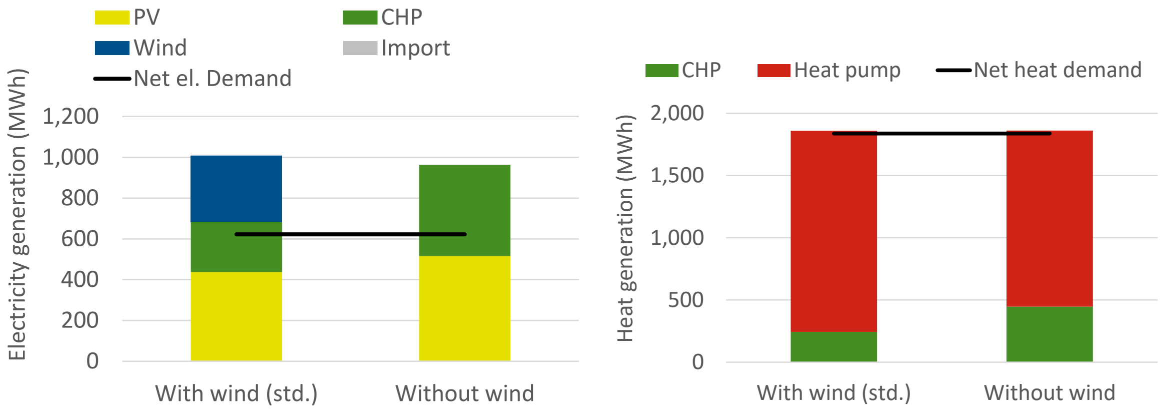

Figure 43 Influence of the existence of wind energy potential on annual supply of electricity (left) and heat (right) in district A variant 1

The sensitivity analysis shows that the use of regional wind energy potential offers significant advantages for the district. This conclusion applies in particular if no heat/power cogeneration is available or if electricity imports make a relevant contribution to electricity generation alongside solar and wind.

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