Temperature-level dependent modeling of energy flows at the quarter level

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Abstract: The overarching goal is the development of cross-sectoral planning and operational principles for energy networks that combine the most efficient energy utilization with an optimized integration of volatile local provision of energy such as electricity or heat. This is explicitly focused on the examination of new quarter planning. The modeling and optimization of the resulting energy flows plays a central role in this endeavor. During system modeling, it becomes evident that the temperature level of heat demands is crucial for the overall system optimization. The developed method, considering three temperature levels in heat demand, enables a more detailed examination of the vastly different efficiency profiles of various heat generation technologies.

Keywords: energy system optimization, sector coupling, integrated planning

1 Introduction

Besides the ecological necessity for decarbonization, increasing uncertainties in the energy market have brought economic arguments to the forefront for an accelerated phase-out of fossil fuel imports [1] [2]. With the legal embedding of mandatory minimum shares of renewable energies in heat supply [3], further changes arise, rendering a classical sectoral view (electricity, natural gas, heat) no longer conducive to planning energy infrastructures for new quarters. Due to legal constraints on the use of fossil fuels and fossil natural gas will no longer be available as an energy source in the long term. Consequently, carbon free forms of energy and decarbonized substitution of the energy source need to be considered in the long run. Considering the studies indicating a limited future availability of green methane or hydrogen [4], as well as the low primary energy efficiency of green gases, especially in heating applications [5], the planning of gas networks for heat supply is undergoing critical scrutiny. All these developments must be considered in future quarter energy system planning, which includes all kinds of energy current and its optimization.

2 Methodology

Embedded within the overall quarter planning, energy-based optimization is conducted using a bottom-up approach. Initially individual consumer units such as residential and non-residential buildings are examined and subsequently the results are juxtaposed with clustering to encompass larger system interconnections as blocks or streets up to a whole quarter view. This process involves utilizing time series data of consumption and generation obtained from Geographic Information System (GIS) based quarter plans. Energy-based optimization is performed on these time series, forming the foundation for final network planning which includes dimensions, kind and placing of network devices. This approach enables an overall energy system planning based on land use, facilitating a comprehensive planning framework.

The solution space is simulated at each modeled level, considering relevant technical frameworks for energy provision, conversion and storage. It also takes into account the possibilities for external energy sourcing as shown in Figure 1. Considering its greenfield planning nature, wherein nothing is initially precluded, the entire solution space is characterized by a high degree of openness. Furthermore, various levels are to be considered to, for instance, deduce whether a centralized or decentralized heat supply represents the optimum under the respective conditions. Theoretically, there exist a multitude of diverse combinations, rendering the solution space considerably vast.

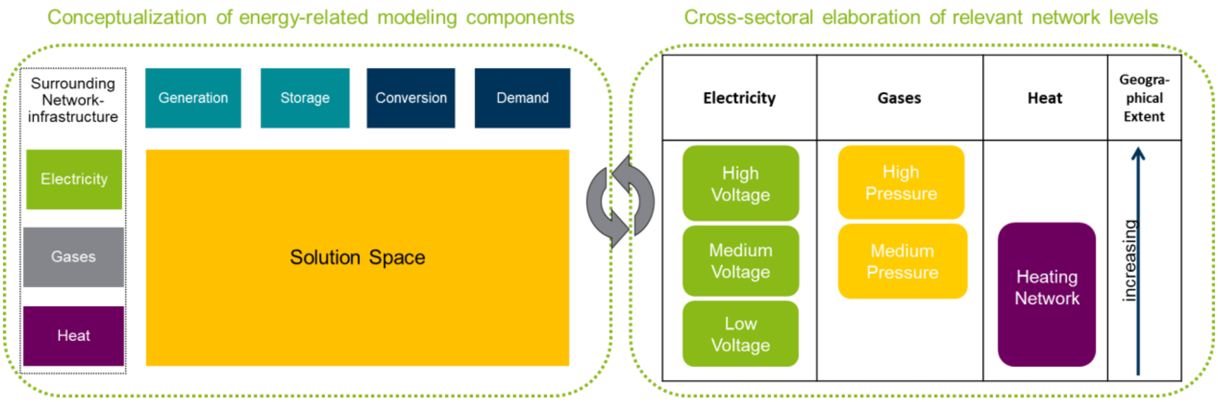

Figure 1: Iteration of energy-based optimization and network planning

The results obtained from this simulation are utilized for planning the required energy infrastructure at the respective level. The level, for instance, may involve optimizing the heating and electricity demand of an individual building, the optimization of a street section, or even the overall system within a quarter. This encompasses non-residential buildings, parking spaces for electric vehicles, as well as potentials for simulating local electricity and heat generation. This may include areas suitable for photovoltaic installations or potential zones for harnessing geothermal energy.

The process involves an iterative approach aimed at identifying and effectively addressing efficiency potentials within the overall system as depicted in Figure 1. Within the calculated results of energy-based optimization the technical most sensible level of network is addressed based on parameters as maximum feed and demand. Results of network planning are matched with key performance indicators as percentage of workload and are given back for an iteration loop to energy-based optimization with a further boundary condition to optimize again. This approach aims to an optimum over both, energy and network, systems.

2.1 Definition of demand structures

In quarters, a diverse array of energy forms may be required. Alongside the electricity demand for direct use in lighting or the operation of various daily-use appliances such as stoves or televisions, there are also heating requirements for building heating and the provision of hot water. In non-residential buildings, e.g. manufacturing facilities, additional needs may arise. This could involve the demand for energy carriers such as hydrogen or methane for conducting chemical processes, or even process heat at a level beyond that of building heating.

Therefore, a distinction is made between the actual demand for a specific form of energy, for example distinguishing between space heating for buildings or methane for the chemical process in a manufacturing facility, and the energy type provided for this purpose, which is then converted into the desired form. In line with this logic, for example, a heat pump (HP) is not considered a heating generation system but rather a conversion system from electricity to thermal energy (Power-to-Heat). Similarly applicable is the concept of a gas boiler (Gas-to-Heat). There is, therefore, a categorization of needs (“demand”), coupled with an additional categorization concerning the provision aspect (“generation” and “transformation”). Over those categories there is always the aspect of efficiency which as to be considered, correctly modeled and optimized. While the efficiency of combustion systems like gas heaters or direct electric heaters remains relatively constant regardless of the desired temperature level, HP solutions exhibit significant efficiency differences depending on source and target temperatures [6], as illustrated by the example of an air-water HP in Figure 2.

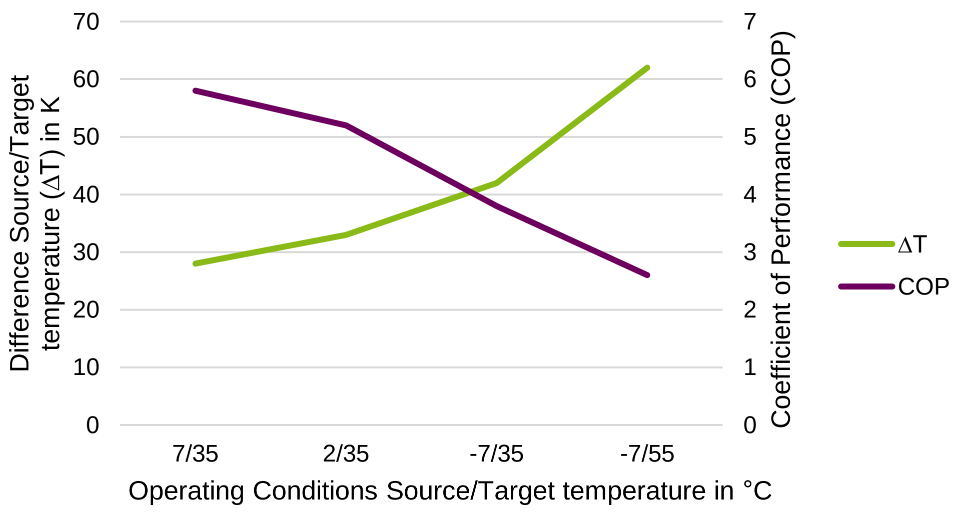

Figure 2: Efficiency profile of an air-water heat pump in different operating conditions (own representation according to [6])

This is primarily attributed to the respective efficiency profiles. Efficiency profiles are defined here as the coefficients of performance or efficiency factors at different operating points of various technologies for heat provision. The measure of efficiency for a HP is the coefficient of performance (COP), which expresses how much heat the system can provide using a certain amount of electricity while utilizing ambient heat. For instance, a COP value of 3 means that 1 kWh of electricity can generate a usable heat quantity of 3 kWh. This measure is comparable to efficiency in other types of systems, although not entirely accurate in all physical aspects, hence the introduction of the COP measure. As the temperature difference (ΔT) between the source and target temperatures increases, it is evident that the COP drops significantly, which is not the case for combustion-based heating systems like gas, hydrogen, or pellet heaters. There is a clear discrepancy in the behavior of different heating systems at various target temperatures, consequently influencing the optimization process directly. Due to these interrelationships, it becomes evident that the temperature level of heat demands is crucial for overall system optimization. Based on this observation, a distinction is made between levels for low-temperature building heating, high-temperature building heating and process heat. Low-temperature building heating is defined as a temperature of maximum 50 °C (“heat 1”), which is typical for low temperature building heating as it is typically built in modern office and residential buildings [7]. High- temperature building heating is defined as a temperature of maximum 95 °C (“heat 2”), which is demanded for heating in older facilities [7], facilities which have a special demand on sterilization of water [8]. The third Temperature-Level (“heat 3”) is defined as temperatures >95 °C which are necessary for industrial demands as melting metals or plastics. There is designed compatibility between the temperature levels (see Figure 3), allowing, according to technical logic, higher temperatures to be utilized to cover heat demands at lower temperature levels with minimal energy input, while the reverse is not feasible. Various technologies for heat provision are modeled and parameterized with their capabilities and efficiency profiles at these different levels as shown in Figure 3.

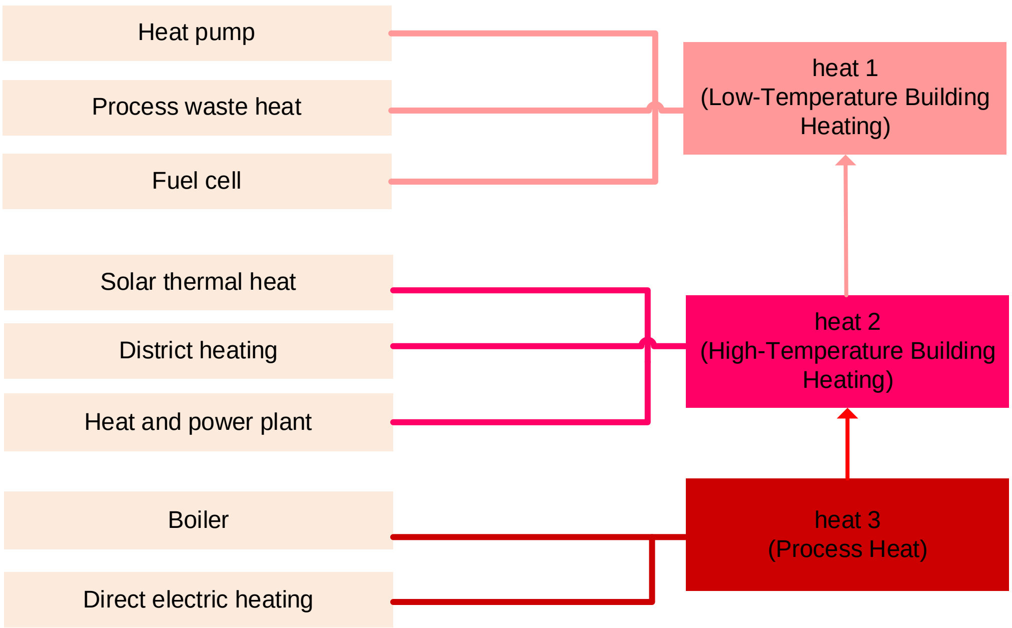

Figure 3: View of the temperature level modeling

This approach involves a systematic modeling of the heat demands within the quarter, considering the specific requirements concerning necessary temperatures while other demand types as electricity are addressed without further distinction. This stands in contrast to established supply planning for heat infrastructure, which primarily relies on the demand for kilowatt-hours and the transportation of corresponding amounts of energy. This represents a significant difference in approach.

2.2 Structure and functionality of the energy model

Supply options through external infrastructure, such as existing district heating systems, are also considered. The python-based Open Energy Modeling Framework (OEMOF) is utilized for conducting energy-based optimization, providing a toolbox for modeling energy systems. OEMOF is used, because it enables the representation and parameterization of various generation, conversion, and storage facilities, considering relevant technical and economic parameters [9].

The foundational structure of the “buses” in OEMOF is systematically modeled based on the physical demands of consumers in the form of electricity, natural gas, hydrogen, and heat requirements at three different levels as shown in Figure 3. This modeling approach considers the innovative concept of downward-compatible temperature levels, following the logic connection that a low temperature-level demand can be addressed by a high temperature level source without adding energy to the system, but does not work in the other direction without adding any kind of energy.

Energy sources are modeled through the structural component called “sources” encompassing all technologies capable of supplying energy to the quarter. These include not only electricity, natural gas, hydrogen, and district heating networks but also on-site generation facilities within the quarter, such as photovoltaic and solar thermal installations, as well as waste heat potentials for example from industrial processes at corresponding temperature levels. Detailed time series data for rooftop and ground-mounted solar installations are captured to actual available solar potentials, which are integrated into OEMOF. Economic parameters, such as individual feed-in tariffs which for example are provided by the german “Erneuerbare Energie Gesetz” (EEG) [10] for solar electricity into the public grid, are also included in the modeling process to ensure realistic results in commercial considerations.

In contrast to the described source elements (“source”), facilities responsible for providing the required types of energy are defined as conversion facilities (“transformer”). These types of facilities encompass air and soil HP technologies, combined heat and power plants, boilers, electric heating systems, fuel cells, and district heating transfer stations. According to the logic used, a gas boiler is not simply a heat provider or a heater but rather a gas-to-heat converter. The same applies to a HP, which is defined and modeled as an electricity-to-heat converter. this approach accounts the respective scale effects for building technology or power plant units by concerning the sizes of these facilities. Therefore, the same model can be used for optimizing a single-family house as well as for optimizing an entire quarter. This also holds true for the modeled storage technologies (“storage”), such as hot water storage, hydrogen storage, or devices for electricity storage like stationary batteries and electric vehicles.

The outflow of energy from the system is modeled and implemented in the form of "sinks". These elements facilitate introducing customer demands into the system and transferring surplus energy beyond the boundaries of the modeled system to the public infrastructure. The whole solution space can be summarized as shown in Figure 4, which shows the connections between the different kinds of currents and technical devices. The connecting buses are modelled as stripes in this figure, colored in the specific color of energy types.

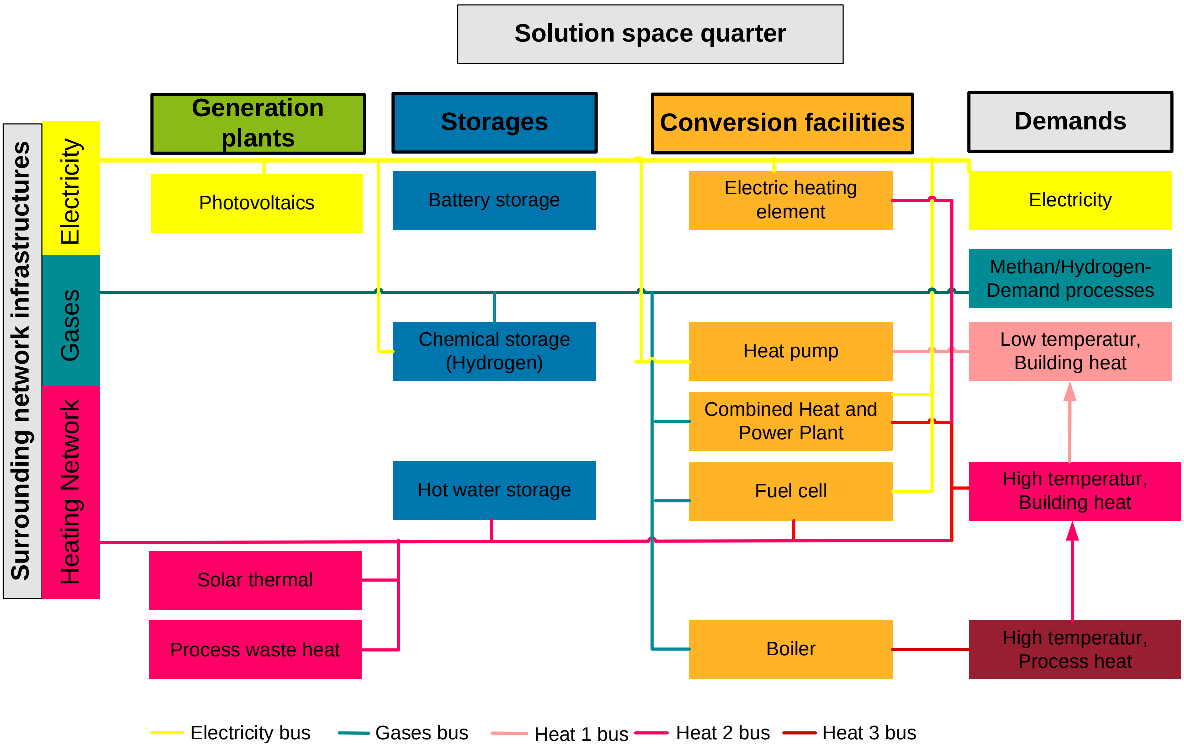

Figure 4: An overview of the solution space in energy-based optimization

The employed methodology and the extensive solution space is feasible to model and optimize energy flows across all relevant scales, from single building to whole quarter level, without the need to resort to a different system environment or to make manual adjustments.

The existing technical characteristics and interdependencies among various technologies are thus linked and modeled across the traditional sectors (electricity, gas and heat). Subsequent optimization is parameterized to the optimization of cost-effectiveness but can also be parametrized to other goals as Carbon dioxide (CO_2) optimization or degree of self-sufficiency by adjusting the corresponding parameters. The methodology employed herein exhibits notable advantages, particularly in terms of its inherent flexibility, so that changes in costs of assets can be recognized same as specific demands set by quarter developing companies.

3 Results

The developed method, considering three temperature levels in heat demand, also allows for a more detailed examination of the vastly different efficiency profiles of various heat generation technologies. Initial analyses of the primary energy expenditure of various heat supply systems reveal a significant difference in efficiency concerning the provision of different temperature levels as shown in Figure 5 within a vivid comparison. The calculation for electric driven heating by HP technologies is based on the primary energy factor of public electricity generation in Germany from the year 2022 and is extrapolated to other electricity mixes like the electricity mix aimed by the german government for the year 2030, which contains 80 % of renewable energies and at least 20 % of other resources preferred natural gas. Furthermore, electricity derived entirely from natural gas is also considered, assuming an electrical efficiency of 40 %, which is a lower middle efficiency for power plants driven by natural gas [11]. Furthermore, gas combustion driven boilers are recommended, too. Thermic efficiency of those kind of heating device is between 98 % in condensation mode (applied for “heat 1”) and 93 % in non-condensation mode applied for other types of heat demands [12]. The possibilities and limitations of the utilized technologies are effectively modeled, and energy flows are calculated based on specific quarter requirements and optimization objectives.

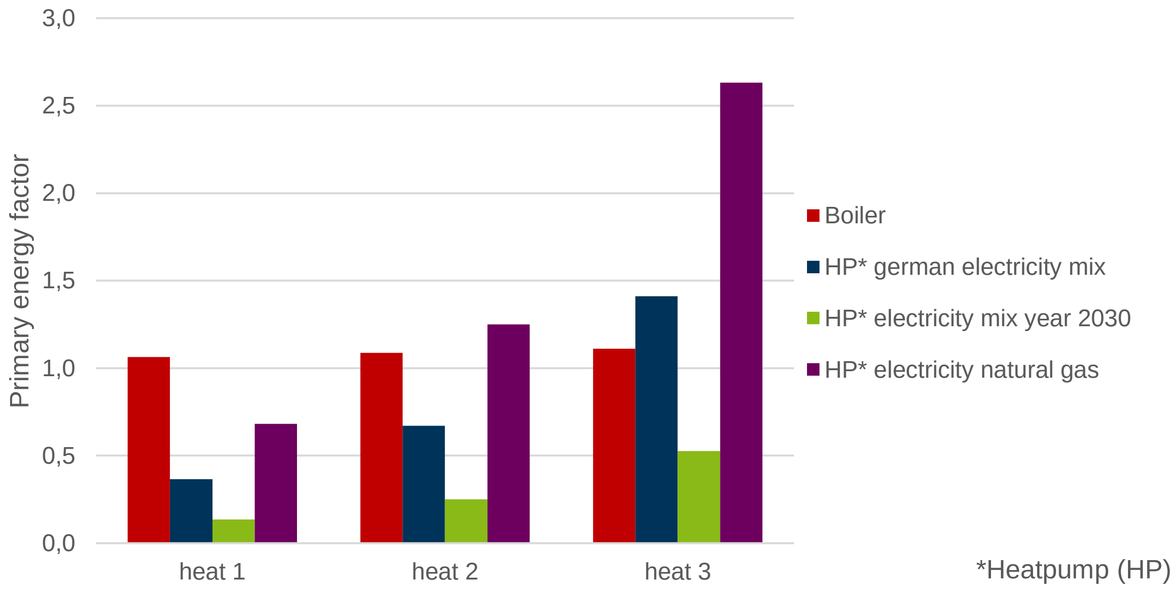

Figure 5: Primary energy factors of typical heat supply systems at different target temperatures

As this example shows there are significant differences in primary energy requirements for providing the respective heat levels. At the temperature level “heat 1”, even the operation of an air-water HP with electricity generated entirely from natural gas exhibits a superior primary energy factor compared to a gas heating system. However, this scenario undergoes a significant change at higher temperature levels. At the “heat 2” level, the combustion process catches up within the gas boiler, whereas for “heat 3”, only electricity with a substantial renewable component in the primary energy factor remains competitive against a gas boiler, because the characteristics of the HP approach those of electric resistance heating as the COP comes close to one at elevated temperature requirements. The outcomes vary considerably depending on the considered temperature level, emphasizing the necessity to account for the specific temperature range in the analysis.

Those initial simulations indicate that the primary energy usage of heat pumps for decarbonizing the building heat sector, which is mainly on “heat 1” level, is significantly lower compared to efficient combustion systems running on natural gas. Combined with an analysis of regulatory requirements for decarbonization as shown in the introduction, it is deduced that planning gas networks in the low-pressure range to supply residential buildings in new quarter is no longer conducive. Research on hydrogen and synthetic natural gas, shown earlier in this paper showing a low efficiency in conversion of green gases form electricity support these findings. Following this result there will be no low-pressure gas network in new quarter planning. This leads to a reduction of complexity and costs.

Building upon these results, the fully integrated overall system optimization for quarter-based planning is being further developed. For this purpose, technical plausibility is examined based infrastructures for further validation on initially using existing quarter. In addition, commercial indicators are validated, and regulatory constraints are considered. Special emphasis is placed on transparency and editability to be able to respond to changing market conditions or specific project requirements in the context of quarter development projects to achieve a good practical usability.

4 Acknowledgment

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