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Potential-risk and no-regret options for urban energy system design — A sensitivity analysis

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ABSTRACT

This study identifies supply options for sustainable urban energy systems, which are robust to external system changes. A multi-criteria optimization model is used to minimize greenhouse gas (GHG) emissions and financial costs of a reference system. Sensitivity analyses examine the impact of changing boundary conditions related to GHG emissions, energy prices, energy demands, and population density. Options that align with both financial and emission reduction and are robust to system changes are called "no-regret" options. Options sensitive to system changes are labeled as "potential-risk" options.

There is a conflict between minimizing GHG emissions and financial costs. In the reference case, the emission-optimized scenario enables a reduction of GHG emissions (−93%), but involves higher costs (+160%) compared to the financially-optimized scenario.

No-regret options include photovoltaic systems, decentralized heat pumps, thermal storages, electricity exchange between sub-systems and with higher-level systems, and reducing energy demands through building insulation, behavioral changes, or the decrease of living space per inhabitant. Potential-risk options include solar thermal systems, natural gas technologies, high-capacity battery storages, and hydrogen for building energy supply.

When energy prices rise, financially-optimized systems approach the least-emission system design. The maximum profitability of natural gas technologies was already reached before the 2022 European energy crisis.

1. Introduction

Urban energy systems play a key role in achieving national and international climate protection goals (Cajot et al., 2017; Shang & Lv, 2023). At the same time, the 2022 energy crisis in Europe (Ruhnau, Stiewe, Muessel, & Hirth, 2023) has shown how quickly some of the most relevant parameters for the design of energy systems may change. Compared to the pre-crisis year 2021, the average wholesale price of electricity in the European Union (EU) has increased by an average of +220% (European Commission, 2023a), and the wholesale price of natural gas by +300% (European Commission, 2023b), while the natural gas consumption decreased by −10% (European Commission, 2023b). Such changes in system parameters are expected to have a strong effect on energy systems, their design, and their optimization (Pfenninger, 2014).

Numerous studies have addressed recommendations for the optimal design of urban energy systems with a focus on financial costs (e.g., Bertilsson, Göransson, & Johnsson (2023), Steingrube et al. (2021)) or greenhouse gas (GHG) emission reduction. The focus on GHG reduction usually has a specific goal, such as meeting EU climate protection targets (e.g., Capros et al. (2019)), enabling "climate neutral" energy supply (e.g., Suppa & Ballarini (2023)), or energy supply with 100% renewable energies (e.g., Danieli et al. (2023)). Studies utilizing optimization models typically prioritize the minimization of a single criterion, while other variables are only simulated but not included in the optimization process. Multi-criteria optimization approaches, in which the conflict between several objectives is examined and necessary trade-offs are identified, are too rarely used (Klemm & Wiese, 2022; Zhang et al., 2018).

Furthermore, upstream and life-cycle energies or GHG emissions required for production, installation, maintenance, and disposal of supply technologies, infrastructure or imported energies are neglected overall in existing urban energy systems (Grubler et al., 2012), particularly in "climate neutral scenarios".

In addition, most energy system models do not consider a strategic uncertainty assessment (Yue et al., 2018). As a result, the impact of

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Abbreviations

ASHP	air source heat pump
CHPP	combined heat and power plant
DH	district heating
EU	European Union
GCHP	ground coupled heat pump
GHG	greenhouse gas
oemof	Open Energy Modeling Framework
PV	photovoltaic
RAM	random-access memory
SESMG	Spreadsheet Energy System Model Generator

changing boundary conditions or assumptions, such as energy prices, upstream emissions, or consumption patterns, on recommended target scenarios is unclear.

Therefore, there is a gap of studies analyzing the full range between the competing objectives of minimization of financial costs and the minimization of GHG emissions. Furthermore, the impact of changing boundary conditions such as energy prices, upstream emissions, and energy demands deserve more attention.

We hypothesize that there are technologies and measures for urban energy systems that can simultaneously reduce GHG emissions and financial costs. Furthermore, we assume that some of these technologies are robust to external system changes and are particularly suitable with regard to constantly changing boundary conditions, while other technologies are especially sensitive to changing boundary conditions.

To answer this hypothesis and to fill the described literature gap, this study analyzes the impact of aleatory uncertainties (Kiureghian & Ditlevsen, 2009) on optimized urban energy supply systems. A multi-criteria approach was conducted, optimizing the energy supply of an reference urban energy system for both financial costs and GHG emissions. Subsequently, sensitivity analyses were conducted by re-running the optimization with varying system parameters and examining the changes in investment and dispatch decisions. The focus of the sensitivity analyses lays on uncertainties of energy prices (natural gas, electricity, hydrogen, combined), GHG emissions (total GHG emissions, GHG emissions of imported electricity and hydrogen), various energy demands (electricity, heating), and population density on urban energy systems.

Parameter changes that exert a major impact on urban energy system design will be identified. Specifically, we will analyze which technologies and measures are particularly robust to parameter changes (**no-regret options**) and which are particularly sensitive (**potential-risk options**) in terms of both financial costs and climate protection targets.

The application of a reference case with representative structure with respect to different consumption and energy sectors, as well as investment and dispatch decisions, ensures transferability of the results to other urban energy systems. This especially applies to countries of the EU, which share similar challenges and strategies for energy supply and market structures for energy pricing, driven by decisions of the European Commission (Kanellakis, Martinopoulos, & Zachariadis, 2013).

2. Material and methods

In this study, a transferable reference case (Section 2.1) was optimized using a multi-criteria optimization model (Section 2.2). Subsequently, several sensitivity analyses were conducted to evaluate the robustness of individual supply options (Section 2.3).

2.1. Reference case

Urban energy systems differ strongly from each other with regard to their building structure (e.g., building density or construction year), usage types (e.g., residential, commercial, or industrial), existence of energetic potentials (e.g., geothermal potentials), and many more. Therefore, it is not feasible to define a generally valid reference system. To ensure the highest possible degree of transferability, a real-world energy system (Fig. 1) was chosen as the reference case for this study. It meets numerous pre-defined requirements; it consists of several sub-systems, i.e. buildings of various usage types (residential, commercial, sports facilities, garages), different types of residential buildings with differing population densities, roof orientations, and geothermal potentials. It is assumed that up to three identical adjacent buildings share the same energy supply technologies. These buildings are therefore clustered in the model. The geographical coverage was chosen so that each optimization run could be solved in under 24 h using the chosen methodology.

The aim of the model is to optimize the energy supply regarding both financial costs and GHG emissions. Various investment and dispatch decisions for several kinds of technologies can be carried out by the model. In the course of this optimization, it is assumed for simplicity that all buildings are in an unrenovated state and that investment costs apply for every technology considered. Table 1 provides an overview of which technologies and measures can be considered. Electricity, natural gas and hydrogen imports can be carried out as dispatch decision. Financial costs and upstream GHG emissions occurring for the imported energy are taken into account. Electricity produced in individual sub-systems, i.e. buildings or central energy supply units, can either be used internally, transferred to other sub-systems in return for grid fees, or sold/exported to outside the system.

The maximum capacities of photovoltaic (PV) and solar thermal usage is restricted by the limited availability of suitable roof areas and their respective orientations. The possible load profiles are calculated individually for each surface by the model (see Section 2.2) taking into account the given location (latitude, longitude, and altitude) and orientations (azimuth and tilt) of the roofs. For every roof area, there is area competition for either PV or solar thermal systems. Only one of these systems can be installed on each surface.

2.2. Model description

The Spreadsheet Energy System Model Generator (SESMG) (Klemm, Becker, Tockloth, Budde, & Vennemann, 2023), a modeling tool based on the Open Energy Modelling Framework (oemof) (Krien et al., 2023), was used. The Gurobi solver (Gurobi Optimization, LLC, 2022) was employed.

Model properties: The applied perfect foresight model used a bottom-up analytical approach and mathematical approaches of linear programming and mixed-integer programming (for district heating (DH) only) for investment and dispatch optimization. Several energy sectors (electricity, heat, natural gas, hydrogen) and demand sectors (residential, commercial, sports facilities) were covered. A house sharp spatial resolution, a hourly temporal resolution, and a time horizon of one year were applied.

Multi-criteria optimization: The epsilon-constraint method (Mavrotas, 2009) is applied for multi-criteria optimization. Therefore, a primary optimization criterion (financial costs in €) is minimized by the models' solving algorithm. In a second model run, a secondary optimization criterion, GHG emissions in g CO_2-equivalents (in the following just referred to as g), is minimized. To combine both optimization criteria, the secondary optimization criterion is used as a constraint, which is tightened in several model runs until the minimum of the secondary criterion is reached. In consideration of this constraint, the model runs are minimized with respect to the primary criterion. The

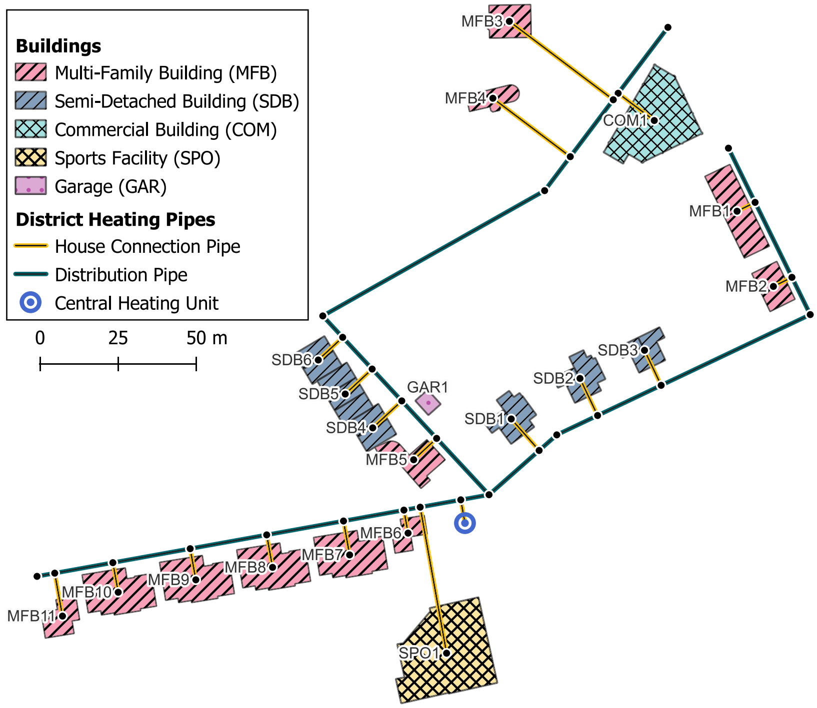

Fig. 1. Reference case area in Herne (Germany) to which the sensitivity analyses were applied. The shown DH pipes corresponds to the position of pipes for which investment decisions could be carried out during the optimization process.

Table 1
Technologies and measures which were considered for the optimization of the test cases energy supply. *If PV and solar thermal systems may potentially be installed on the same surface, only one of the two technologies will be considered during the optimization.

Technology	Centr.	Decentr.	Technology	Centr.	Decentr.
natural gas heating	x	x	DH network	x	
ASHP	x	x	natural gas CHPP	x	
GCHP		x	electrolysis	x	
electric heating		x	hydrogen CHPP (fuel cell)	x	
PV system*		x	methanation	x	
solar thermal system*		x	natural gas storage	x	
battery storage		x	hydrogen storage	x	
wall insulation		x	battery storage	x	x
roof insulation		x	thermal storage	x	x
window insulation		x	sub-system electricity exchange	x	
DH connection		x			

Acronyms: ASHP = air source heat pump, centr. = centralized, CHPP = combined heat and power plant, decentr. = decentralized, GCHP = ground coupled heat pump.

calculated semi-optimal scenarios act as “best-known Pareto points” and are combined to a “Pareto front” (Konak, Coit, & Smith, 2006). A reasonable third optimization criterion would be to minimize the effective energy demand (Klemm & Wiese, 2022). However, demand reductions based on sufficiency measures do not counteract any of the other two optimization criteria and are usually very likely to improve them. Therefore, the reduction of the effective energy demand has not been used as a tertiary optimization criterion, but was separately treated in the sensitivity analysis.

Emissions approach: For the consideration of GHG emissions, the adapted consumption based emissions approach by Klemm and Wiese (2022) was considered. All emissions that are caused for the provision of the energy consumed in the system were taken into account, but not for energy exported to neighboring systems.

Model simplification: The applied model is spatially and temporally highly resolved and contains a large number of linear and binary investment decisions. In order to solve this model with the available random-access memory (RAM) and run-time, it was necessary to make some model simplifications. By carrying out temporal simplified pre-models using weekly time-averaging (averaging and merging of ten weeks each), preliminary results were created for each model run (“pre-modeling” Klemm, Wiese, & Vennemann (2023)). These preliminary results were used to identify technologies that are not profitable at all. Based on this, these technologies were removed from the main-model (“technical pre-selection” Klemm, Wiese, & Vennemann (2023)). Within the main-model, temporal-slicing (Klemm, Wiese, & Vennemann, 2023) considering every fourth day was used.

Data: Weather data from the German Weather Service for the year of 2012 (Deutscher Wetterdienst, 2020), which was an average solar year (Deutscher Wetterdienst, 2022), was used. A detailed description of all system parameters as well as how the individual components in the system are connected to each other is given in Appendix A. Due to the European energy crisis, energy prices were subject to strong fluctuations at the time this study was carried out. Pre-crisis values were therefore used for the entire model to take account of a settled market situation with regular ratios and proportions.

2.3. Sensitivity analyses

Emerging uncertainties can be categorized into aleatory and epistemic uncertainties (Kiureghian & Ditlevsen, 2009). Epistemic uncertainties can be avoided by improving the model quality through the use of additional data (parametric uncertainties) or by refining the model (structural uncertainties) (DeCarolis et al., 2017). Improving the model quality is the only way of quantifying epistemic uncertainties (Pfenninger, 2014). Aleatory uncertainties cannot be reduced by improved model quality (Kiureghian & Ditlevsen, 2009), yet they can be quantified by deterministic or stochastic approaches (DeCarolis et al., 2017). Within this study, the deterministic approach of sensitivity analysis was applied. This approach enables the identification of "critical model features that lead to important changes" (DeCarolis et al., 2017) in system design and furthermore to "extract insights that are robust to" (DeCarolis et al., 2017) changing system conditions. These insights can be used to better define system design with regard to changing key system parameters.

The financially-optimized energy supply scenario and the GHG emission-optimized supply scenario were calculated and used as reference scenarios for the sensitivity analyses. Several gradations were applied for each sensitivity parameter. For each of these gradations, a new optimization run was performed and thus an adjusted energy supply scenario was calculated. A total of 10 sensitivity analyses were applied, which can be divided into three categories:

- GHG emissions
  - total GHG emissions
  - GHG emissions of imported electricity
  - GHG emissions of imported hydrogen
- financial costs
  - natural gas price
  - electricity price
  - hydrogen price
  - combined energy price
- effective energy demands
  - electricity demand
  - heating demand
  - population density

For the variation of restrictions regarding the **total GHG emissions**, the epsilon-constraint method (see above) was applied to calculate a financially-optimized scenario (0% GHG reduction), an emission-optimized scenario (100% GHG reduction), and nine further scenarios in 10% GHG reduction steps in-between. The financially-optimized and emission-optimized scenarios form the reference cases for the further sensitivity analyses

The average GHG emissions of the German electricity mix, considered as the **GHG emissions of imported electricity**, were initially varied in six gradations (0, 50, 75, 125, 150 and 200%) and supplemented by a further gradation (25%) for a more precise resolution.

Typical GHG emissions of green hydrogen were considered in the reference case for the **GHG emissions of imported hydrogen**. This value was initially varied in six gradations (0, 50, 75, 200, 500, and 1000%) and supplemented by two further gradation (300 and 400%) for a more precise resolution.

The individual energy **prices of natural gas, electricity and hydrogen** were varied in six gradations (0, 50, 75, 200, 500, and 1000%) deviating from the respective reference value. As the interactions between the prices of individual energy forms are particularly strong (Frydenberg, Onochie, Westgaard, Midtsund, & Ueland, 2014), the prices have been varied together (combined energy prices). Therefore, it was assumed that the costs for the import of all energy carriers vary linearly with the same gradations as above.

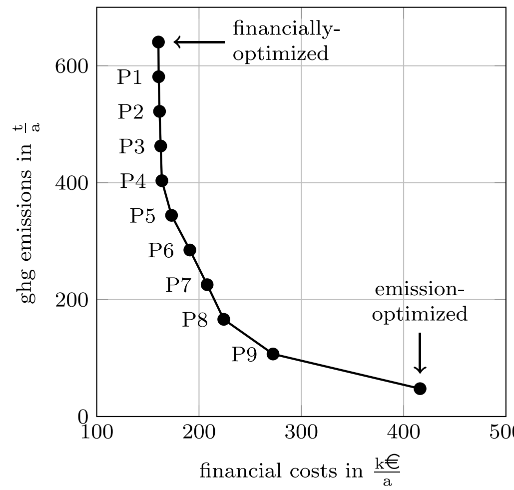

Fig. 2. Pareto front composed of optimized energy systems for an urban district with different weighting of primary (financial costs) and secondary (GHG emissions) optimization criteria. The financially-optimized scenario causes financial costs of 160 k€/a and annual GHG emissions of 641 t/a. Starting from there, up to the P4 scenario a significant reduction in emissions (−37%) with only a slight increase in financial costs (+2%) is enabled. From P5 on, the additional costs increase more, with the largest increase occurring between P9 and the emission-optimized scenario. The emission-optimized scenario enables a significant reduction of GHG emissions to 48 t/a (−93%), but also increased financial costs of 416 k€/a (+160%).

The individual **electricity demand** as well as the **heating demand** for every individual building based on consumption behavior was varied in six gradations (0, 50, 75, 125, 150 and 200%) deviating from the respective reference values.

The **population density** was varied by the number of inhabitants per housing unit in six gradations (0, 50, 75, 125, 150 and 200%) deviating from the reference case. The number of inhabitants was rounded to integer numbers or zero for each housing unit.

3. Results

3.1. Reference case and impact of GHG reduction goals

The Pareto front in Fig. 2 includes the financially-optimized scenario, the GHG emission-optimized scenario, and nine further Pareto scenarios in between. A reduction of GHG emissions by −93% may be realized compared to the financially-optimized case, but a reduction to zero is not possible due to life-cycle emissions of technical facilities.

Within the **financially-optimized scenario**, the heat supply is primarily based on (centralized) natural gas technologies, and the electricity is supplied by a heat-driven natural gas combined heat and power plant (CHPP), as well as PV systems (Fig. 3). The net internal electricity production exceeds the electricity demand; therefore, large shares are exported. However, electricity still needs to be imported in small quantities at times when the internal production is insufficient.

With **decreasing total GHG emissions**, the heat supply is progressively decentralized. At the same time, the heating demand is reduced due to building insulation, and electricity demand increases due to electrification of the heat supply. In P5 and P6, flexible electricity supply is low while the heating demand is met by heat pumps that are adjusted to the load profiles of PV systems. Thermal storages are utilized more frequently, although not with a higher capacity than in other scenarios, to match heat supply with consumption. As the GHG emissions constraint increases, the natural gas CHPP production is designed to zero in P7, and the electricity demand increases to its maximum in P9 due to heat pump usage. In scenarios P6 through P9, major shares of electricity are imported. In the emission-optimized scenario, battery storages and hydrogen CHPP are considered instead. P9 is the only scenario, where a combination of electrolysis and hydrogen storage are used for electric load shifting.

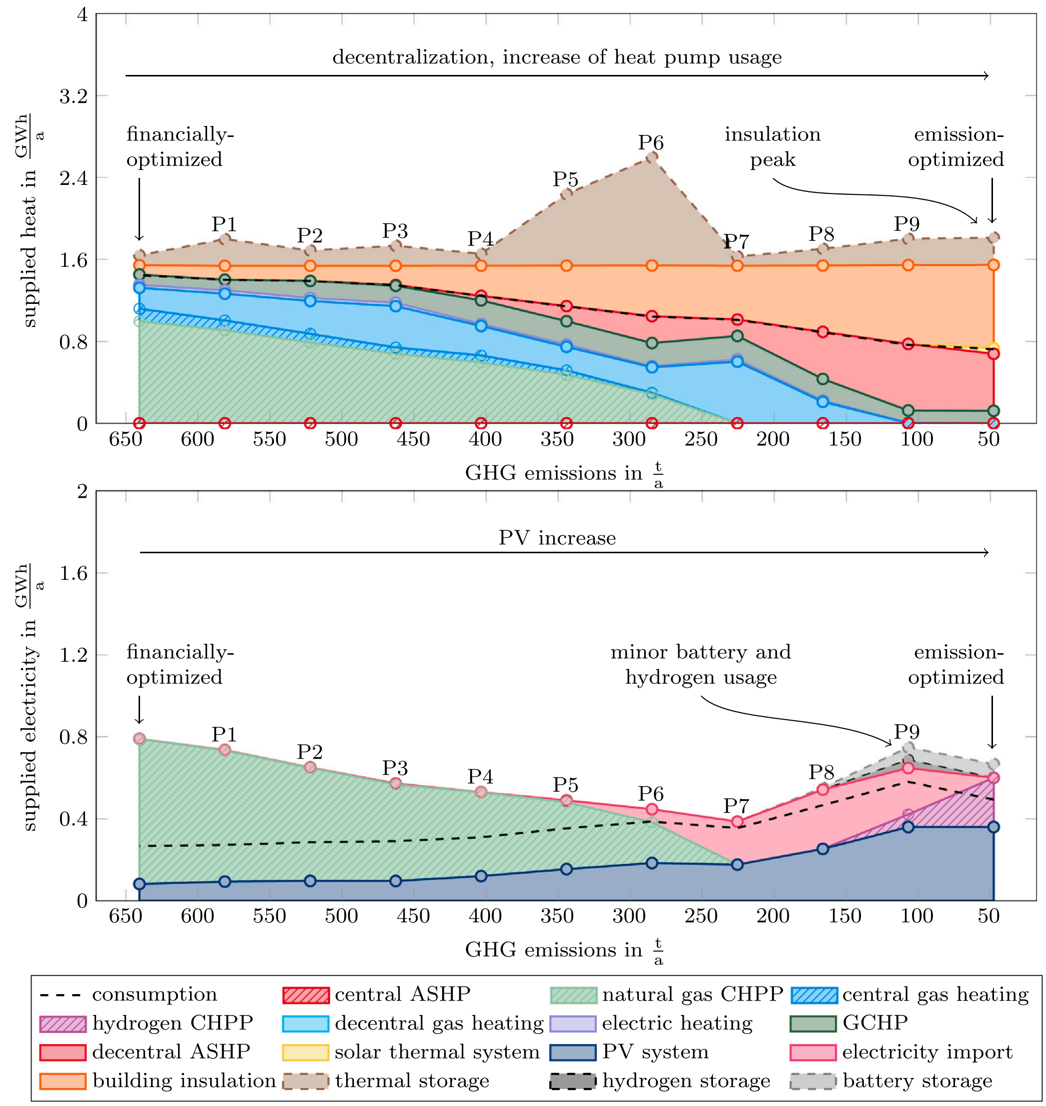

Fig. 3. Heat (top) and electricity (bottom) supply in the optimized reference case scenario in dependency on total GHG emissions. In the financially-optimized case, the heat supply is primarily based on natural gas with a major share (13/19 buildings) of centralized heat supply. Building insulation (reducing the heating demand by 6%), GCHPs (7% of the heating demand), and electric heating (2% of the heating demand) technologies are less important. In the emission-optimized case, the maximum possible building insulation enables a reduction of heating demand by −53%, the remaining heating demand being covered by heat pumps (76% ASHPs and 17% GCHPs) and solar thermal systems (7%). Electricity is supplied by PV systems (0.36 GW h/a) and a central hydrogen CHPP (operated purely electrically, 0.24 GW h/a) in combination with battery storages (0.07 GW h/a). Further results are presented in Appendix B.

In the **emission-optimized scenario**, the remaining heating demand of maximum possible insulated buildings is provided by air source heat pumps (ASHPs), ground coupled heat pumps (GCHPs) and solar thermal systems. Decentralized ASHPs are preferred over centralized ones, as heat losses (about 8%) and life-cycle emissions for the construction of DH pipes are thus avoided. PV systems, hydrogen, and CHPP are used for electricity supply and battery storages for load shifting. The PV potential is not fully utilized in any of the scenarios, especially with respect to PV modules deviating more than 65° from the south axis. Solar thermal systems were only considered in the emission-optimized scenario on surfaces without PV potential.

3.2. Sensitivity: GHG emissions of imported energy

Within two individual sensitivity analyses, the GHG emissions of (1) imported electricity and (2) imported hydrogen between 0% and 200%, respectively 1000%, of the reference values.

In the **financially-optimized scenario**, varying the GHG emissions of imported electricity (Appendix C) and hydrogen (Appendix D) has no effect on investment or dispatch decisions, as no financial parameters are changed. However, absolute GHG emissions are reduced, corresponding to the extent of respective energy imports.

Within the **emission-optimized scenario**, the import of electricity and the use of hydrogen CHPP for electricity supply are in direct competition (Appendices C and D). Electricity imports increase in emission-optimized scenarios when the GHG emissions of imported electricity (reference 366 g/kW h) drops below the footprint of electricity supplied by the hydrogen CHPP (120 g/kW h in the reference case) or even by PV systems (27 g/kW h). The hydrogen CHPP is applied within the optimization for GHG emissions of imported hydrogen up to 132 g/kW h (reference 44 g/kW h). However, if non-green hydrogen is imported, electricity imports are preferred over the hydrogen CHPP (this includes when the imported electricity is used for hydrogen production). The heat supply, apart from the cases of emissions-neutral imports of electricity or hydrogen, remains unchanged.

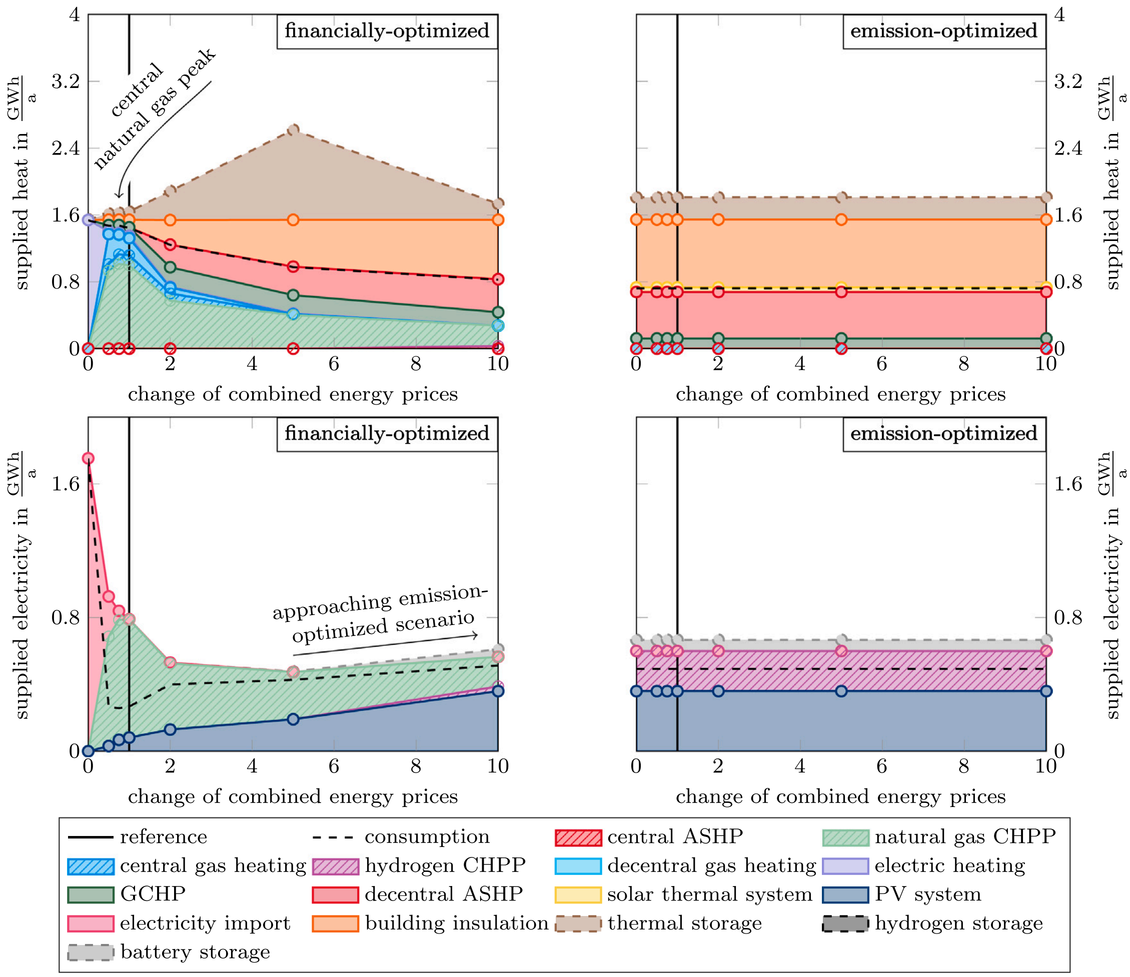

Fig. 4. Supplied heat (top) and electricity (bottom) in the financially- (left) and emission-optimized (right) reference case in dependency on changing combined energy prices. The financially-optimized reference case corresponds to the maximum of natural gas-based central heat supply with 13 out of 19 buildings being connected and a heat supply share of 84%. With energy prices ten times higher than the reference case, energy is supplied with building insulation (reducing demands by −46%), thermal storages (shifting 23%), GCHP (supplying 19%), ASHP (48%), natural gas CHPP (30%), and hydrogen CHPP (4%) for heat supply and PV systems (supply of 73% of the internal demand with additional export of temporal surpluses), natural gas CHPP (34%), hydrogen CHPP (6%) and battery storages (shifting 9%) for electricity supply. Further results of the sensitivity of combined energy prices are visualized in Appendix H. Results for individual variations of natural gas, electricity and hydrogen are shown in Appendix E, F, and G.

3.3. Sensitivity: Energy prices

Within four individual sensitivity analyses, the prices for (1) natural gas, (2) electricity, (3) hydrogen, and (4) all together (combined energy prices) were varied between 0% and 1000% of the respective reference values.

The comparison of the effects of changes in combined energy prices (Fig. 4) with those in individual energy prices shows that the effect of changing natural gas prices (Appendix E) dominates the **financially-optimized scenario**. The centralized natural gas technologies have their maximum viability between 75% and 100% of the reference case. At higher natural gas prices, reduced CHPP capacities lead to higher shares of PV systems and electricity imports. However, the increase in electricity prices (Appendix F) has a damping effect on this trend, and even at 1000% of the reference combined energy prices, four buildings remain connected to the natural gas-based DH network. Reduced CHPP electricity supply is replaced by increased PV usage, small battery storages, and (only in the case of 1000% combined energy prices) a hydrogen CHPP. In scenarios with the least internal electricity production, thermal storages are again utilized more intensively by increasing storage frequency. Overall, with an increase of combined energy prices, the energy supply moves towards the emission-optimized scenario.

The usage of PV systems is replaced when electricity prices decrease below the production costs of PV (0.08–0.14 €/kW h, depending on orientation). For the hypothetical scenario of all energy prices decreasing to near-zero, the electricity price has a dominant effect and the use of electric heating systems for heat supply rises sharply shortly before the case of a cost-free energy.

The **emission-optimized scenario** is not affected, because changes in energy prices do not affect the minimization of GHG emissions within the applied model.

3.4. Sensitivity: Energy demands

Within two individual sensitivity analyses, the (1) electricity demand and the (2) heating demands have been varied between 0% and 200% of the respective reference values.

Changing electricity demands (Appendix I) only affects the electricity supply, not the heat supply. The influence is limited primarily to the dimensioning of PV systems in the **financially-optimized scenario** and to hydrogen CHPP and battery storages in the **emission-optimized scenario**. If the behavioral based electricity demand is reduced to zero, the absolute electricity demand and thus the electricity supply has an offset which is caused by the electrified heat supply.

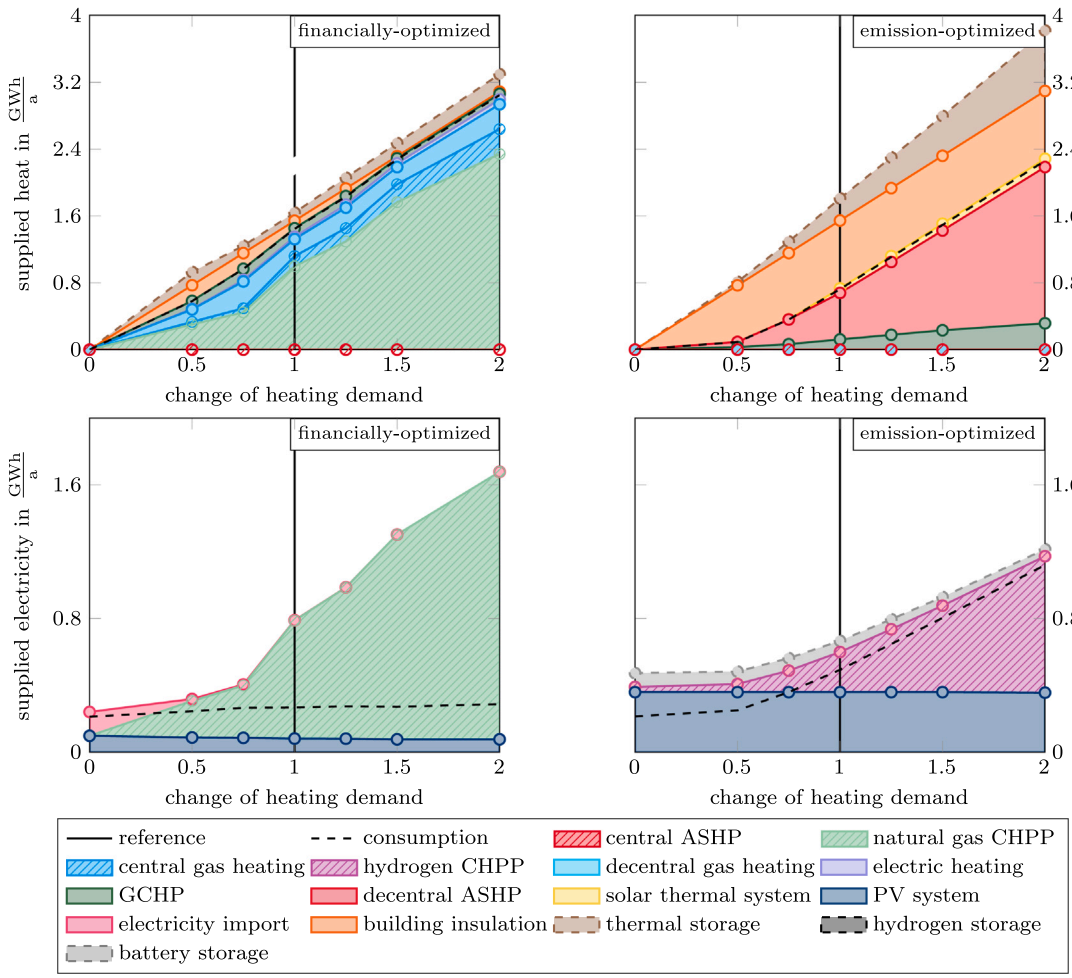

Fig. 5. Supplied heat (top) and electricity (bottom) in the financially- (left) and emission-optimized (right) reference case in dependency on changing heating demands. In the financially-optimized scenario, the heat is primarily supplied by natural gas regardless of the heating demand, but the number of buildings connected to the DH network varies from five (at a maximum of 75% of the reference heating demand) to 16 buildings (at a minimum of 150% of the reference heating demand). At the same time, with higher heating demand based on consumption behavior, less insulation is considered, because the viability of natural gas-based central heat supply increases. In all emission-optimized scenarios apart 0% heating demand, the maximum possible building insulation is used. The use of the considered supply technologies (ASHP, GCHP, solar thermal systems, and thermal storage) changes linearly with heating demand Further results of the sensitivity of heating demands based on consumption behavior are visualized in Appendix J.

Changes in heating demand (Fig. 5) based on consumption behavior affect optimization for both heat and electricity supply. In the **financially-optimized scenario**, with decreasing heating demand, the shares of insulation, GCHPs, and decentralized gas heating systems increase. As soon as the electricity production through heat driven natural gas CHPP in combination with PV systems cannot meet the electricity demand from a certain state on, electricity imports increase. With increasing heating demand, the profitability of natural gas-based central heating supply increases due to increased spatial density of heating demands and more buildings being connected to the DH network. In the **emission-optimized scenario**, the usage of ASHP, GCHP, solar thermal systems, and thermal storages changes linearly with heating demand. The usage of hydrogen CHPP changes linearly for heating demands above 50% of the reference value, due to the sector coupled system. Below this value, the system remains unchanged and PV systems relatively dominate. As the heating demand increases, flexibility is mostly provided by increased thermal storages, leading to reduced battery storage usage.

Both reductions of electricity and heating demands enable a significant reduction in financial costs and GHG emissions. However, the reduction of the heating demand has a larger impact since it makes up a larger share on total energy demand.

3.5. Sensitivity: Population density

Within this sensitivity analysis, the population density was varied between 0% and 200% of the respective reference values.

The population density primarily influences the absolute electricity demand (Appendix K) for both financially and emission-optimized scenarios. Therefore, the system design is rather robust against changes in population density. However, the specific energy supply per inhabitant changes significantly (Fig. 6), and the relative impact on both specific financial costs and GHG emissions is enormous.

4. Discussion

4.1. Potential-risk and no-regret options

The analysis showed that the level of system's permitted GHG emissions, the price of imported energy, especially natural gas, as well as absolute heat and electricity demands have the highest influence

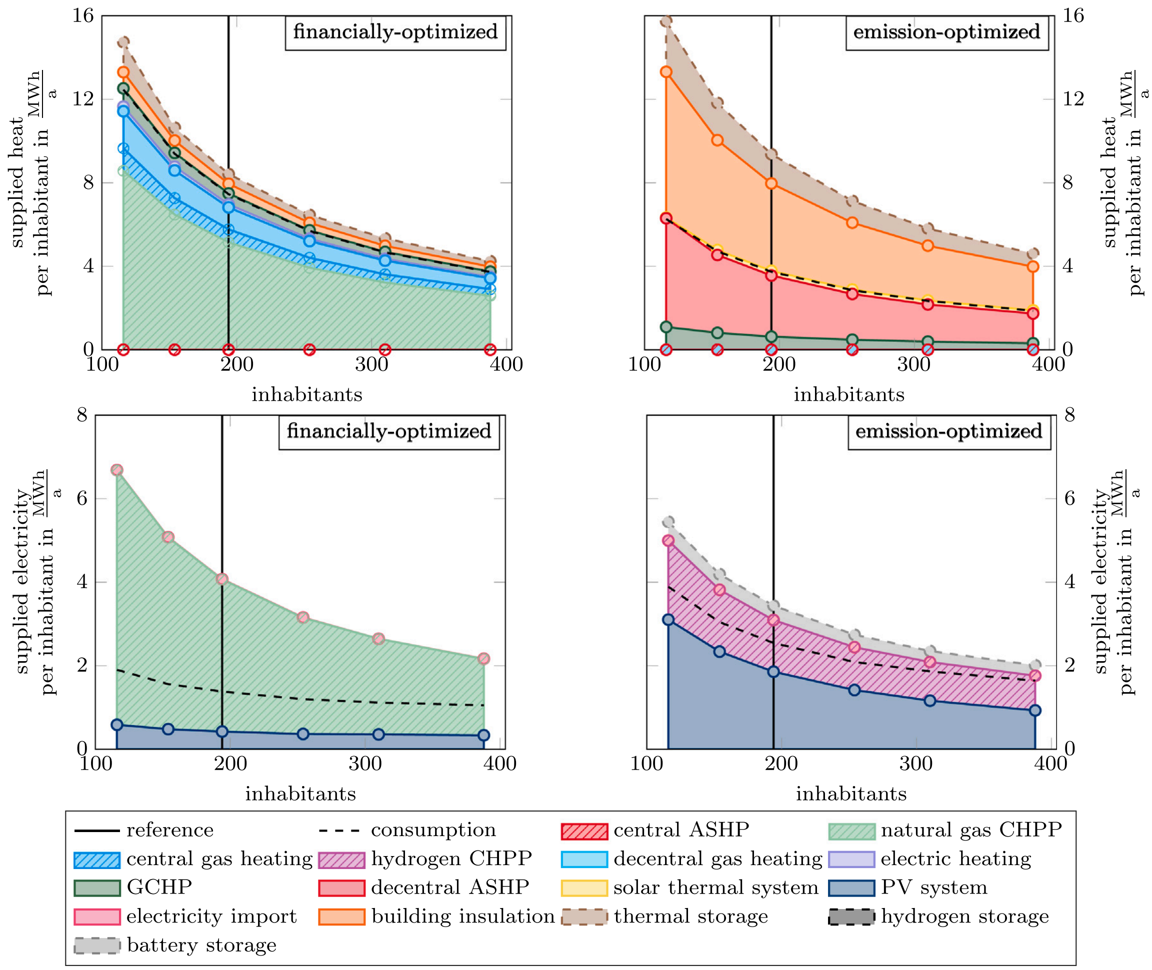

Fig. 6. Supplied heat (top) and electricity (bottom) per inhabitant in the financially (left) and emission-optimized (right) reference case in dependency on changing population density. The curves are not linear, since the energy demand of non-residential buildings remains unchanged as a base demand The change in population density has limited impact on the absolute optimized energy supply. Mainly the absolute use of PV systems in the financially-optimized case and hydrogen CHPP in the emission-optimized case change, but the specific use per inhabitant remains rather constant Further results of the sensitivity of population density are visualized in Appendix K.

on the design of optimized urban energy systems. Measures and technologies for optimizing urban energy systems can be considered as **no-regret options** if the sensitivity analyses of this study have proven their suitability for both financial and emissions-based optimization and if they are robust to parameter changes. Expected trends such as GHG mitigation requirements, rising energy prices, or declining GHG emissions from imported electricity are particularly relevant. Measures and technologies that are particularly sensitive to these changes can be considered as **potential-risk options**.

The implementation of **building insulation** is a no-regret strategy for financially-optimized decarbonization of urban energy systems. The optimal amount of building insulation used in a system is subject to trends of energy prices, requested reductions in total GHG emissions, and trends of energy demands, and will yet more likely increase than decrease under any predictable future scenarios. The obvious positive climate effect may be diminished by a high climate intensity of the material used for insulation. Reducing energy demands (heat and electricity) by **behavioral and structural changes** is a no-regret measure with regard to reducing both financial costs and GHG emissions. It is expected that the mix of supply options will remain largely unchanged, while the sizing of the technologies will change in response to demand. Only the share of central heating, which is dependent on the spatial density of heating demands, decreases with demand reductions. Reduction of **living space per inhabitant** by adapting the population density is a no-regret strategy, as both financial costs and GHG emissions per inhabitant are reduced while the design of optimized systems remains largely unchanged.

The use of **decentralized natural gas technologies** for heat supply is very sensitive to the analyzed system changes, and their usage is therefore a clear potential-risk option. With respect to predictable trends such as increasing total GHG emissions mitigation requirements and energy prices, their usage is partially or even completely reduced in optimized scenarios. The usage of **decentralized heat pumps** for heat supply in turn steadily increases or at least remains at the same level. As far as heat potentials can be used both central and decentral, decentralized heat pumps allow a more viable use compared to centralized heat pumps due to less heat losses, investment costs, and life-cycle emissions of DH pipes. The usage of heat pumps, especially decentralized ones, is therefore a clear no-regret option.

The viability of implementing new **DH networks** is very sensitive on total GHG emissions, energy prices, and heating demands. Therefore, the exact connectability of buildings to DH networks should be analyzed in detail and be planned with caution. The generalized implementation of DH networks for entire areas, for example, in the context of a connection obligation, carries a high potential-risk.

The optimum size of the **PV systems** varies, but a certain amount with a region-specific maximum azimuth deviation from the south axis is highly robust. This maximum azimuth deviation increases with additional restrictions on total GHG emissions and increasing energy prices. PV systems within the acceptable deviation are no-regret technologies. However, using **solar thermal systems** on surfaces where viable PV usage is an option is a possible-risk option. The usage of PV systems is superior to solar thermal systems with regard to both financial cost and GHG emission reduction.

Exchanging electricity with higher-level energy systems by exporting electricity surpluses and importing deficits is a no-regret strategy, which was applied in each of the optimized scenarios examined. It reduces the need for local electricity storage capacities and oversized plants to meet peak loads. However, this approach may be limited due to transmission capacities and the ability of neighboring and higher-level systems to provide the necessary load exchange. For emission optimized systems, the GHG emissions of imported electricity must furthermore be comparable to or lower than internal electricity production. Fewer restrictions apply to the **local exchange** of locally produced (renewable) electricity between sub-systems. It is a no-regret strategy which reduces necessary storage capacities and, by avoiding electricity imports, financial costs and GHG emissions.

As long as such local exchange of electricity between sub-systems is possible, **battery storages** are only suitable for certain cases of total GHG emission minimization, but not for financial optimization at all. Their usage in optimized systems is furthermore sensitive on GHG emissions of imported energy (electricity and hydrogen) and the system's energy demands (electricity and heat). In combination with the conflict with the robust measures of electricity exchange on various levels, the implementation of large battery storages thus carries a potential-risk. Due to lower life cycle GHG emissions, **thermal storage systems** are more robust for shifting volatile electricity supply with regard to system changes, especially in the case of electrified heat supplies. Depending on the type of heat supply, either centralized or decentralized thermal storage for electric load shifting is therefore a no-regret option.

Green **hydrogen-powered CHPP** is not viable from a financial perspective. It is especially sensitive to the system's absolute energy demands, and its capability for emission reduction is only viable if GHG emissions of imported electricity are higher than electricity supplied by the hydrogen CHPP. The use of hydrogen is therefore a potential-risk option, and the use of non-green hydrogen is no option for system optimization at all.

4.2. Comparison with recent literature

Numerous existing studies suggest different technologies for urban energy systems. Some of these recommendations are consistent with the results of our study. However, there are also contradictions (Klemm, 2023).

Consistent research validates the necessity of Klemm (2023)

- **decreasing energy demands** through high levels of building insulation (Capros et al., 2019; Kranzl et al., 2022) and adjustments to consumption behavior (Sperber, Frey, & Bertsch, 2022),
- the **phase-out of natural gas** usage (Kranzl et al., 2022),
- **electrification** of heat supply (Arabzadeh, Mikkola, Jasiūnas, & Lund, 2020; Capros et al., 2019), especially through **heat pumps** (Arabzadeh et al., 2020; Kranzl et al., 2022),
- use of **thermal storage** for electrical load shifting (Arabzadeh et al., 2020; Ding, Lyu, Lu, & Wang, 2022), and
- the preference for the use of **PV systems** over **solar thermal systems** on suitable roof surfaces (Oliveira, Sousa, & Kotoviča, 2022).

There is also consensus that the use of **hydrogen** for building energy supply can generally enable a reduction of GHG emissions in the case of green hydrogen usage (Capros et al., 2019; Klemm, 2023), but only be viable at very low hydrogen prices (Klemm, 2023; Wietschel et al., 2023).

On the other hand, the current literature lacks a clear consensus on the recommendation for increased electricity exchange between sub-systems and higher-level systems. While some studies argue for greater autarky among sub-systems (Mehta & Tiefenbeck, 2022; VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V, 2022), others propose enhanced exchange between individual systems (Arabzadeh et al., 2020; Bundesnetzagentur, 2017). This study adds to the debate by highlighting the importance of electricity exchange, both within sub-systems and with higher-level systems (Klemm, 2023).

Previous recommendations regarding the viability of **DH networks** for optimized systems differ from our results. This can be explained by different assumptions about system conditions which are not considered in this study (Klemm, 2023):

- Positive effects arise when high building density makes decentralized heat pumps impractical or when only centrally available heat sources are used, such as deep geothermal (Romanov & Leiss, 2022), waste heat (Jodeiri, Goldsworthy, Buffa, & Cozzini, 2022), or river/sea water (Volkova, Koduvere, & Pieper, 2022).
- Investment costs for DH networks may be neglected in some models, if DH networks already exists and if they are depreciated.
- The relevance of new DH networks may increase when the exchange of thermal energy between sub-systems is facilitated (Tockloth, 2024) with the emergence of "5th generation DH and cooling systems" (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; García-Céspedes, Herms, Arnó, & de Felipe, 2022).

When examining energy systems in residential buildings individually, it is commonly recommended to incorporate **battery storage**, often highlighting enhanced self-sufficiency or the financial benefits to individual buildings (Bertsch, Geldermann, & Lühn, 2017; Klemm, 2023; Koskela, Rautiainen, & Järventausta, 2019; Schopfer, Tiefenbeck, & Staake, 2018). However, when compared to sector-coupled thermal storages and local electricity exchange, batteries have limited potential to robustly optimize urban energy systems, although they can improve non-optimized systems (Klemm, 2023). The overall benefit of battery storages might increase with bi-directional charging for electric vehicles and the resulting potential to employ electric battery storage for urban load shifting (Klemm, 2023).

4.3. Limitations and transferability

The model is subject to the common problems in energy system modeling of uncertainty of input data (DeCarolis et al., 2017; Keirstead, Jennings, & Sivakumar, 2012; Pfenninger, 2014). To maintain transparency, all model parameters used in this study are openly accessible (Appendix A). The applied configuration of model-based methods for reducing computing requirements have led, in past studies, to an underestimation of the viability of heat pumps and PV systems (Klemm, Wiese, & Vennemann, 2023). Therefore, their role as potential-risk decisions may even have been underestimated in the presented analysis. The viability of battery storages has been underestimated in the past as well Klemm, Wiese, & Vennemann (2023). The fundamental decision whether a battery storage should be used or not is unaffected, but the question of what capacity to use is affected (Klemm, Wiese, & Vennemann, 2023). Therefore, the general decision between thermal and battery storage is not affected and the recommendations derived in this study remain valid.

Various consumption sectors of urban energy systems were examined. The mobility sector, however, was outside the scope of this study due to the complexity of modeling the consumption profiles and utilization potentials. The mobility sector is a distinct research field on its own (Klemm, 2023). However, future models should analyze possible synergies and conflicting goals resulting from the rising integration of e-mobility into urban energy systems (see Section 4.2).

The applied multi-objective optimization aims to reduce both system-wide economic costs and greenhouse gas emissions (Klemm, 2023). If all stakeholders of urban energy systems (e.g., inhabitants, utilities, and administration) take on territorial social responsibility by transforming their energy system within the scope of this multi-objective optimization and fully exploiting the sustainable potential of the local energy system, they can actively contribute to achieving the GHG reduction goals of the EU (Mussawar, Urs, Mayyas, & Azar, 2023). However, the optimization for system-wide financial costs aims to minimize the aggregated costs for all stakeholders, without considering the distribution of these savings among the individual stakeholders (Klemm, 2023). It is important that individual stakeholders receive benefits from the system, otherwise there may be too much resistance against the realization of recommendations made. Therefore, recommendations for legislative adjustments must be developed in collaboration with policy makers which contribute to this process at municipal, regional and national level (Klemm, 2023).

The results of this study are particularly applicable to urban energy systems in EU member states, especially for western and central Europe, based on the characteristics of market structures, transition goals (Kanellakis et al., 2013), climate conditions, consumption structures, and energetic potentials (Bódis, Kougias, Jäger-Waldau, Taylor, & Szabó, 2019; Ciancio, Salata, Falasca, Curci, Golasi, & de Wilde, 2020; Hurter & Schellschmidt, 2003). In a wider perspective, statements on (1) decisions between centralized and decentralized energy supply, (2) the requirement of sector-coupling, (3) the relationship between (non-)flexible energy provision and storage facilities, (4) the interaction between (sub-)systems for energy exchange, (5) the interaction between strategies of efficiency, consistency, and sufficiency for fulfilling sustainability goals, as well as (6) the identification of GHG reduction potentials at low financial costs are expected to be widely transferable independently of differing input conditions of other regions.

Although market structures are comparable in the mentioned regions, absolute energy prices may differ significantly. For instance, electricity prices for households are +75% higher in Denmark and −60% lower in France than in Germany (end of 2022, European Union (2023)). It can, however, be assumed that similar sensitivity effects occur, although they shift horizontally along the price scale. For example, there is also a maximum profitability of natural gas supported central heat supply (Fig. 4) if natural gas prices are lower than in Germany; it just requires a higher relative price increase for it to be exceeded.

5. Conclusion and outlook

The analysis on design of financially- and emission-optimized urban energy systems has identified the following **no-regret options**, which are robust against external drivers such as changing energy prices and GHG emissions of imported energy:

- reducing **relative and absolute energy demands** by behavioral and structural changes, building insulation, and reducing living space per inhabitant
- preferred use of **decentralized heat pumps** for heat supply
- using **PV systems** on surfaces with suitable orientations
- using **thermal storages** for electric load shifting
- enabling **electricity exchange** both between sub-systems and with higher-level energy systems

On the other hand, the following **potential-risk options** are particularly sensitive to changes in permitted GHG emissions, the price of imported energy, especially natural gas, as well as absolute heat and electricity demands:

- using **solar thermal systems** on surfaces which are suitable for PV usage
- **decentralized natural gas** technologies for heat supply
- generalized implementation of **district heating (dh) networks**
- using **high capacities of battery storages**
- **hydrogen** for building energy supply

Additionally, the applied sensitivity analyses revealed some general trends. For instance, the systems optimized for financial efficiency are approaching the design with the lowest emissions. Additionally, the profitability of natural gas technologies has a clear maximum, which was already reached for the reference case before the 2022 energy crisis in Europe.

In order to be prepared for constant system changes in predictable trends, but also for sudden changes, for example in the context of a renewed energy crisis, it is advisable to focus on the mentioned no-regret options and to avoid the possible-risk options when planning urban energy systems. While those pathways are generalizable, detailed analyses of individual urban systems, taking into account all relevant energy sectors, demands and potentials to consider all area-specific synergies, financial constraints and GHG reduction targets are essential.

Furthermore, specific framework conditions that influence energy system planning but go beyond the scope of energy system modeling (like resource use, quality of living) might shift the focus in respective municipalities and thus the preferred supply options.

Based on the results of this study, future results should investigate the impacts of the increasing integration of the mobility sector into urban energy systems and how different business models can enable all stakeholders to benefit from the economically optimized system, e.g. with the help of local energy markets. Furthermore, policy suggestions need to be formulated from municipal to national levels to facilitate the implementation of the model results.

CRediT authorship contribution statement

Christian Klemm: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Peter Vennemann:** Funding acquisition, Supervision, Writing – review & editing. **Frauke Wiese:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christian Klemm reports financial support was provided by Federal Ministry of Education and Research. Frauke Wiese reports financial support was provided by Federal Ministry of Education and Research.

Data availability

All data used are linked in the appendix.

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Appendix A. Model parameters

All parameters and modeling methods used for this study are openly available within the following directories:

- Description of the model structure and all modeling parameters: https://doi.org/10.5281/zenodo.10477476
- Applied version of the Spreadsheet Energy System Model Generator (SESMG): https://doi.org/10.5281/zenodo.8055828
- SESMG model definitions: https://doi.org/10.5281/zenodo.8042239
- SESMG model results: https://doi.org/10.5281/zenodo.8046254

Appendix B. Results: Reference / GHG emissions

See Table 2.

Table 2
Optimized technology capacities in the reference case in dependency on total GHG emissions. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydrogen CHPP in kW	Electroly-sis in kW	Methana-tion in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	Decentral GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydrogen storage in kW h	DH buildings
FO	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
P1	116	91	0	0	0	0	0	112	81	82	0	20	585	0	0	11
P2	100	90	0	0	0	0	0	95	104	84	0	30	628	0	0	8
P3	86	64	0	0	0	0	0	99	127	84	2	29	608	0	0	6
P4	74	92	0	0	0	0	0	43	105	105	11	45	668	0	0	5
P5	61	55	0	0	0	0	0	51	91	134	30	54	682	0	0	4
P6	39	27	0	0	0	0	0	17	124	158	55	54	734	0	0	3
P7	0	0	0	0	0	0	0	32	200	151	49	54	566	0	0	0
P8	0	0	0	0	0	0	0	23	123	216	100	50	728	33	0	0
P9	0	0	0	10	26	0	0	29	2	295	201	28	1392	222	236	0
EO	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix C. Results: GHG emissions of imported electricity

See Fig. 7 and Table 3.

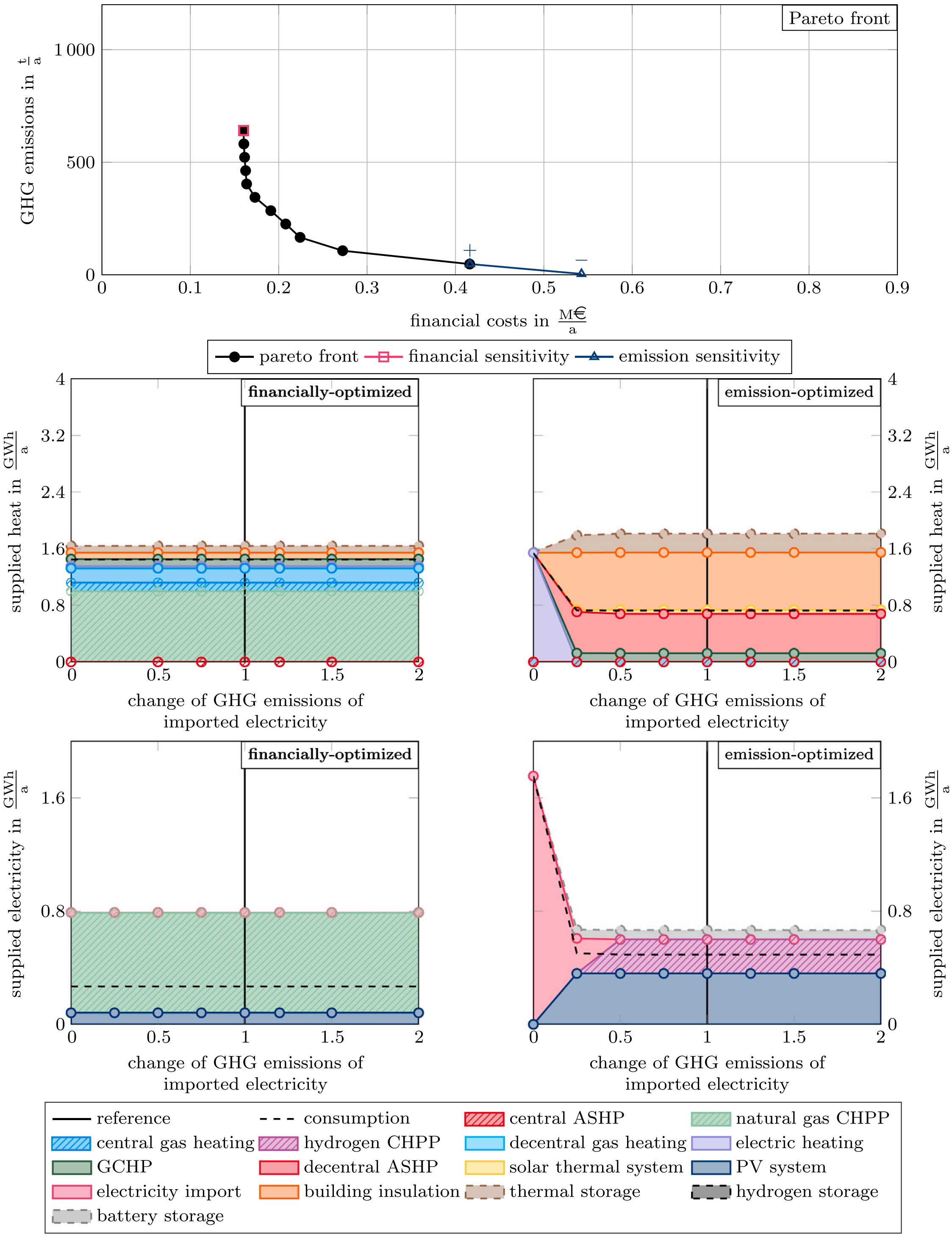

Fig. 7. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (GHG emissions of imported electricity). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". In the emission-optimized case the scenarios including 25%, 50%, 100%, 125%, 150%, and 200% lie on top of each other. **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 3
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of GHG emissions of imported electricity. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydrogen CHPP in kW	Electrolysis in kW	Methanation in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydrogen storage in kW h	DH buildings
FO-0.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-0.25	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-0.5	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-0.75	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.2	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.5	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-2.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
EO-0.0	0	0	0	0	0	0	0	532	0	0	0	0	393	0	0	0
EO-0.25	0	0	0	0	0	0	29	0	0	295	200	28	1378	316	0	0
EO-0.5	0	0	0	185	0	0	56	0	0	295	218	28	1654	347	0	0
EO-0.75	0	0	0	185	0	0	56	0	0	295	218	28	1654	348	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.25	0	0	0	185	0	0	56	0	0	295	218	28	1654	347	0	0
EO-1.5	0	0	0	185	0	0	56	0	0	295	218	28	1654	346	0	0
EO-2.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	347	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix D. Results: GHG emissions of imported hydrogen

See Fig. 8 and Table 4.

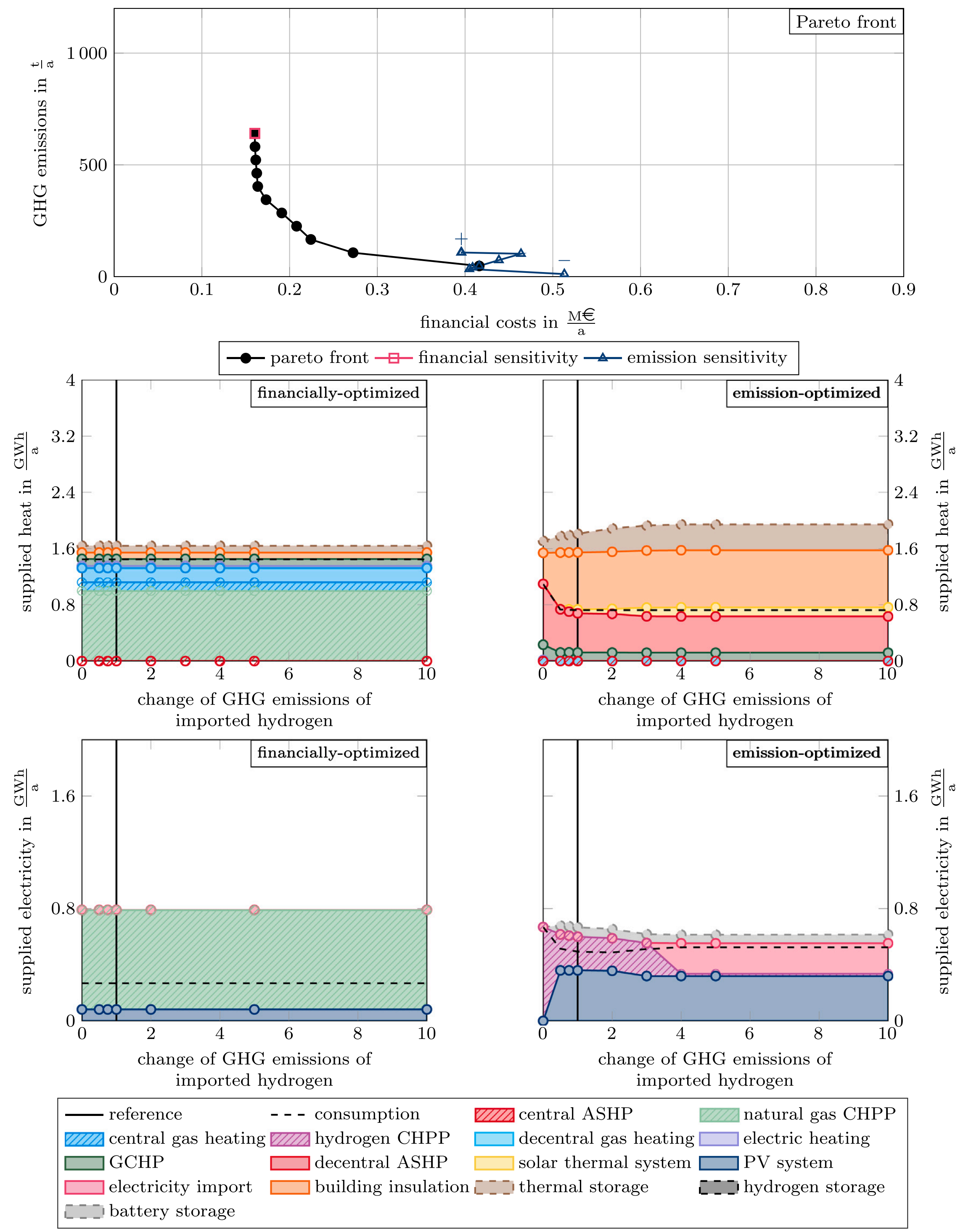

Fig. 8. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (GHG emissions of imported hydrogen). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". In the emission-optimized case the scenarios 400%, 500%, and 1000% lie on top of each other. **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 4
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of GHG emissions of imported hydrogen. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydro-gen CHPP in kW	Electroly-sis in kW	Methana-tion in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydro-gen storage in kW h	DH buildings
FO-0.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-0.5	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-0.75	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-2.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-3.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-4.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-5.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-10.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
EO-0.0	0	0	0	286	0	0	0	73	0	0	243	52	422	0	0	0
EO-0.5	0	0	0	168	0	0	2	0	0	295	196	28	1160	311	0	0
EO-0.75	0	0	0	172	0	0	33	0	0	295	202	28	1403	337	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-2.0	0	0	0	207	62	0	73	62	0	292	286	28	3131	328	167	0
EO-3.0	0	0	0	207	160	0	126	160	0	265	299	28	5962	326	7455	0
EO-4.0	0	0	0	157	160	0	132	160	0	265	320	28	6620	321	9999	0
EO-5.0	0	0	0	157	160	0	132	160	0	265	320	28	6620	321	9999	0
EO-10.0	0	0	0	157	160	0	132	160	0	265	320	28	6620	325	9999	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix E. Results: Natural gas price

See Fig. 9 and Table 5.

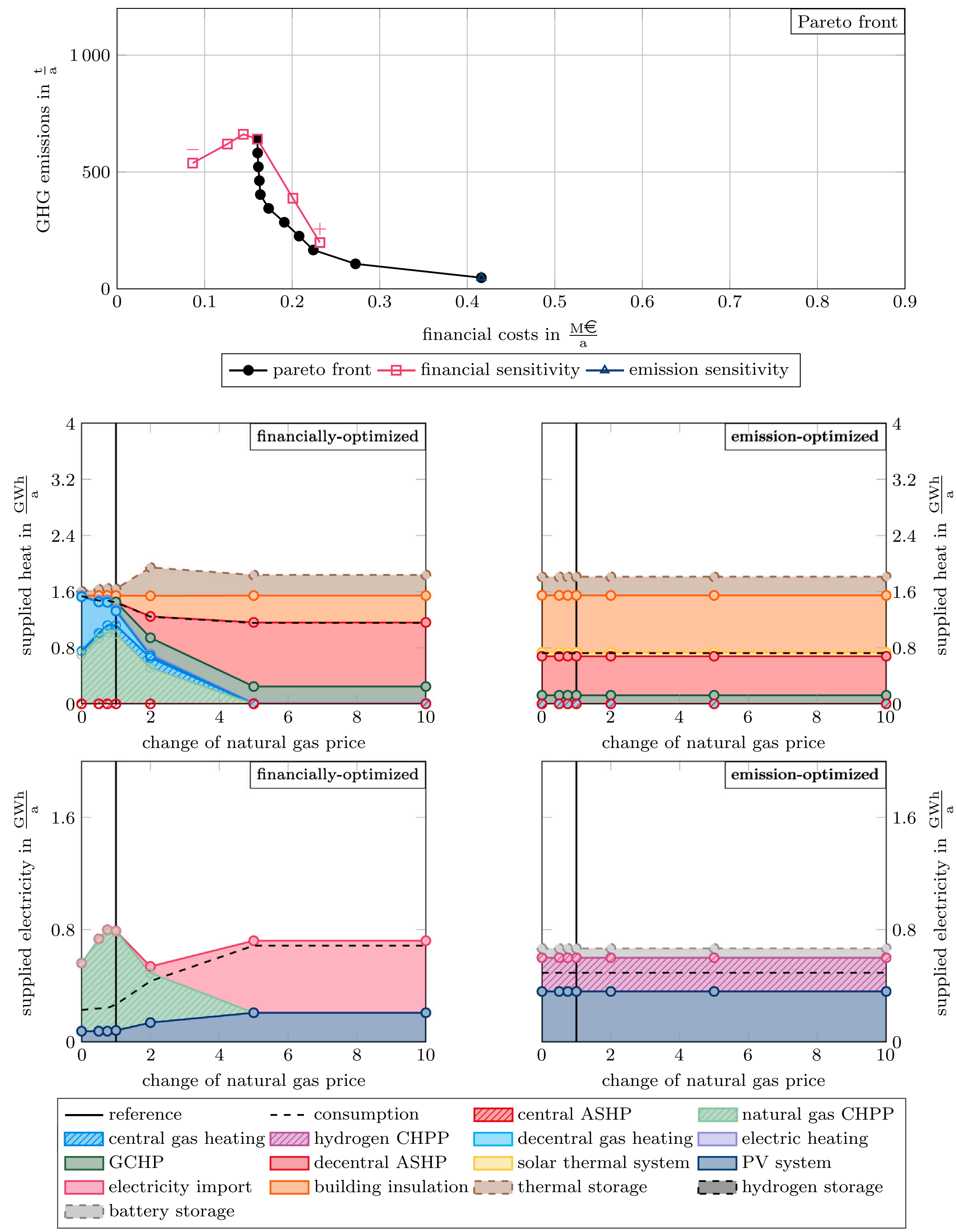

Fig. 9. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (natural gas price). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". In the financially-optimized case the scenarios 500% and 1000% lie on top of each other. **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 5
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of natural gas prices. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydrogen CHPP in kW	Electrolysis in kW	Methanation in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydrogen storage in kW h	DH buildings
FO-0.0	92	96	0	0	0	0	0	73	207	65	0	0	753	0	0	6
FO-0.5	121	81	0	0	0	0	0	116	119	66	0	0	710	0	0	11
FO-0.75	131	97	0	0	0	0	0	121	87	66	0	2	638	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-2.0	57	97	0	0	0	0	0	88	12	121	78	49	657	0	0	6
FO-5.0	0	0	0	0	0	0	0	37	0	176	272	55	1072	0	0	0
FO-10.0	0	0	0	0	0	0	0	37	0	176	272	55	1072	0	0	0
EM-0.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EM-0.5	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EM-0.75	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EM-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EM-2.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EM-5.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EM-10.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix F. Results: Electricity price

See Fig. 10 and Table 6.

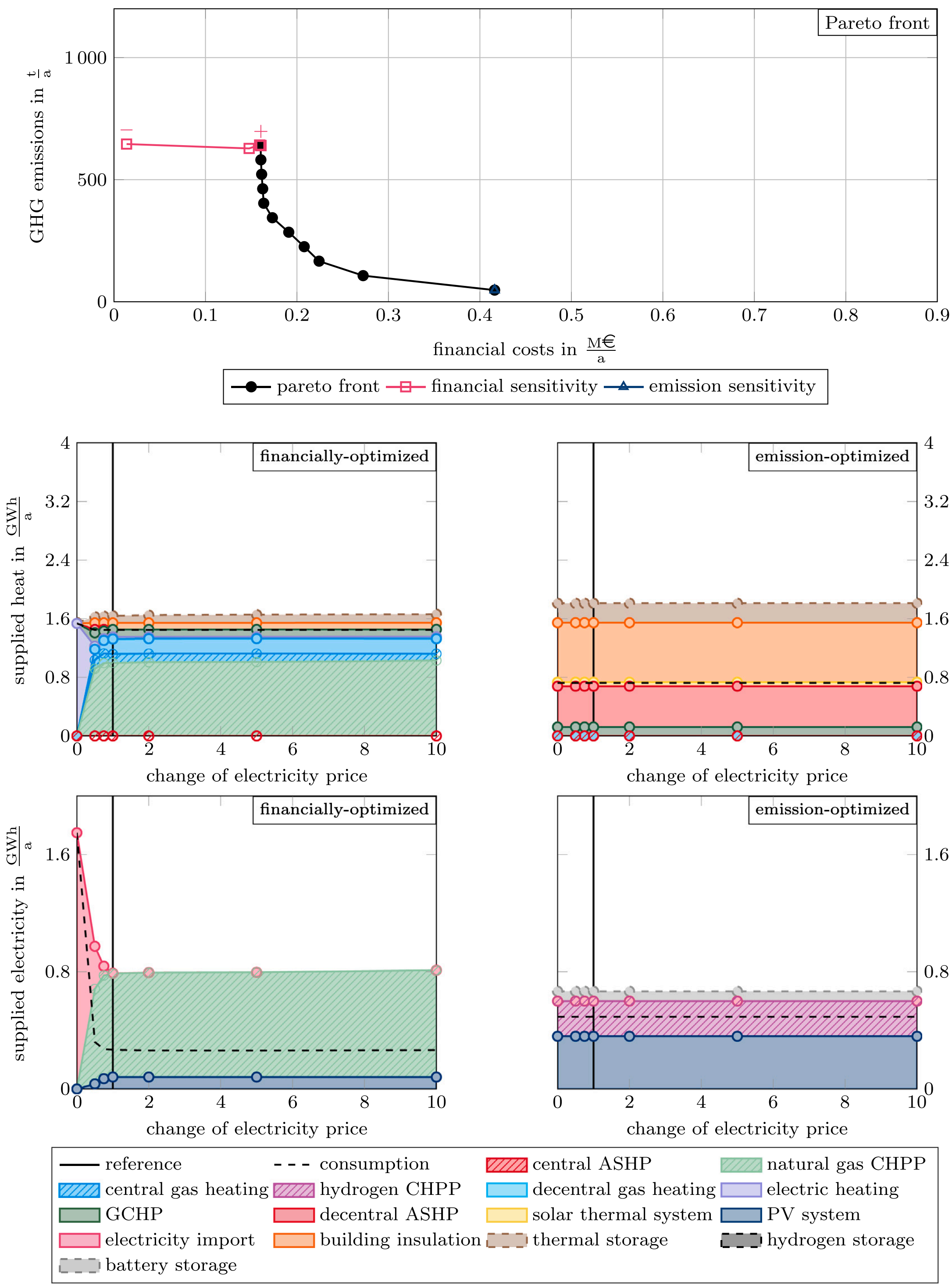

Fig. 10. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (electricity price). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "–", the highest as "+ ". In the financially-optimized case the scenarios 75%, 100%, 200%, 500%, and 1000% lie on top of each other. **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 6
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of electricity prices. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydrogen CHPP in kW	Electrolysis in kW	Methanation in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydrogen storage in kW h	DH buildings
FO-0.0	0	0	0	0	0	0	0	539	0	0	0	0	340	0	0	0
FO-0.5	114	111	0	0	0	0	0	127	42	34	6	34	648	0	0	12
FO-0.75	123	131	0	0	0	0	0	94	56	62	3	19	697	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-2.0	127	117	0	0	0	0	0	100	66	70	0	17	662	0	0	13
FO-5.0	128	116	0	0	0	0	0	99	66	70	0	17	703	0	0	13
FO-10.0	134	94	0	0	0	0	0	111	67	70	0	17	739	0	0	13
EO-0.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-0.5	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-0.75	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-2.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-5.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-10.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix G. Results: Hydrogen price

See Fig. 11 and Table 7.

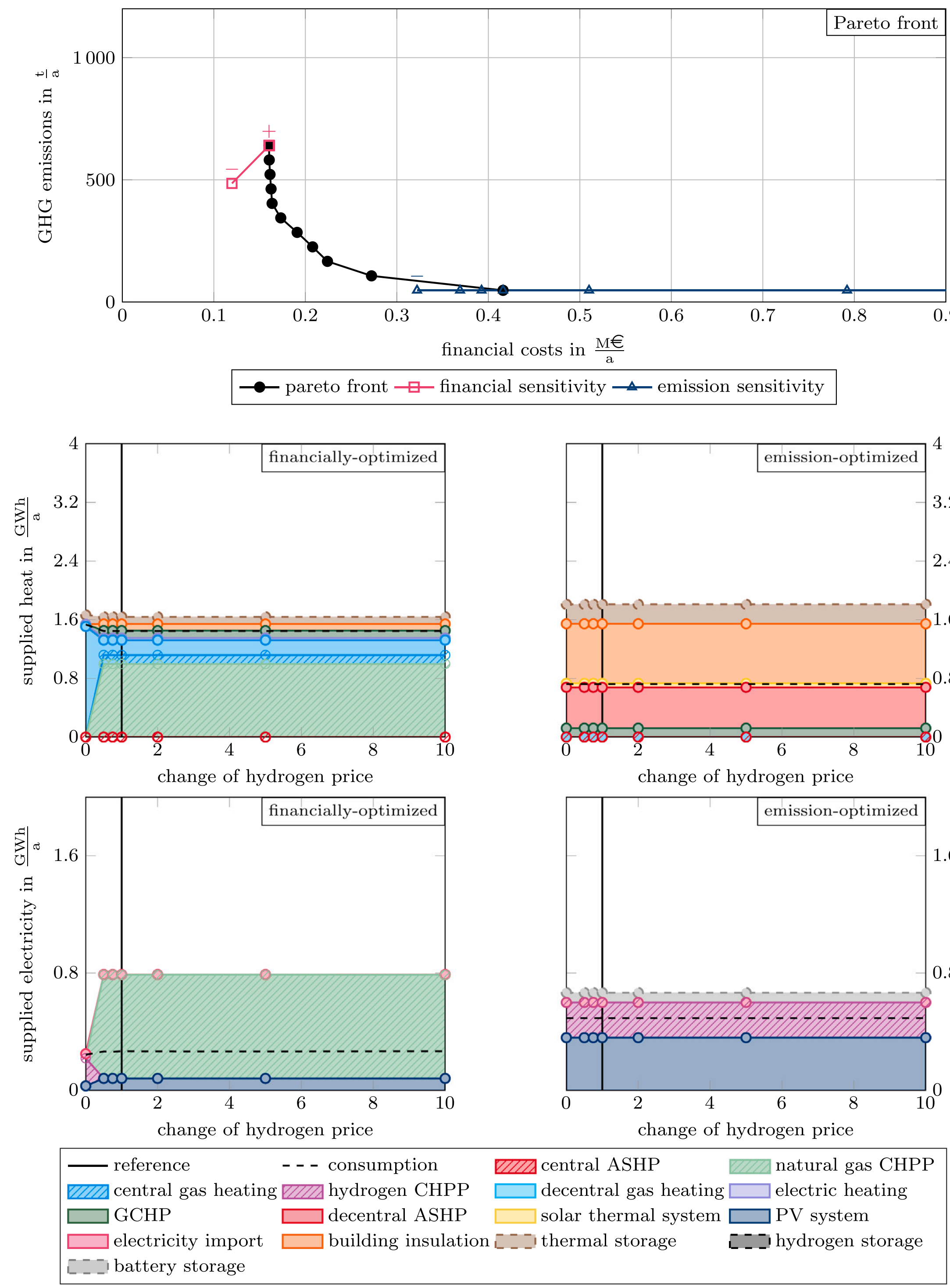

Fig. 11. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (hydrogen price). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "–", the highest as "+ ". In the financially-optimized case the scenarios 50%, 75%, 100%, 200%, 500%, and 1000% lie on top of each other. **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 7
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of hydrogen prices. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydro-gen CHPP in kW	Electroly-sis in kW	Methana-tion in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydro-gen storage in kW h	DH buildings
FO-0.0	0	0	0	30	0	331	0	127	386	29	0	0	706	0	0	0
FO-0.5	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-0.75	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-2.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-5.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-10.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
EO-0.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-0.5	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-0.75	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-2.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-5.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-10.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix H. Results: Combined energy price

See Fig. 12 and Table 8.

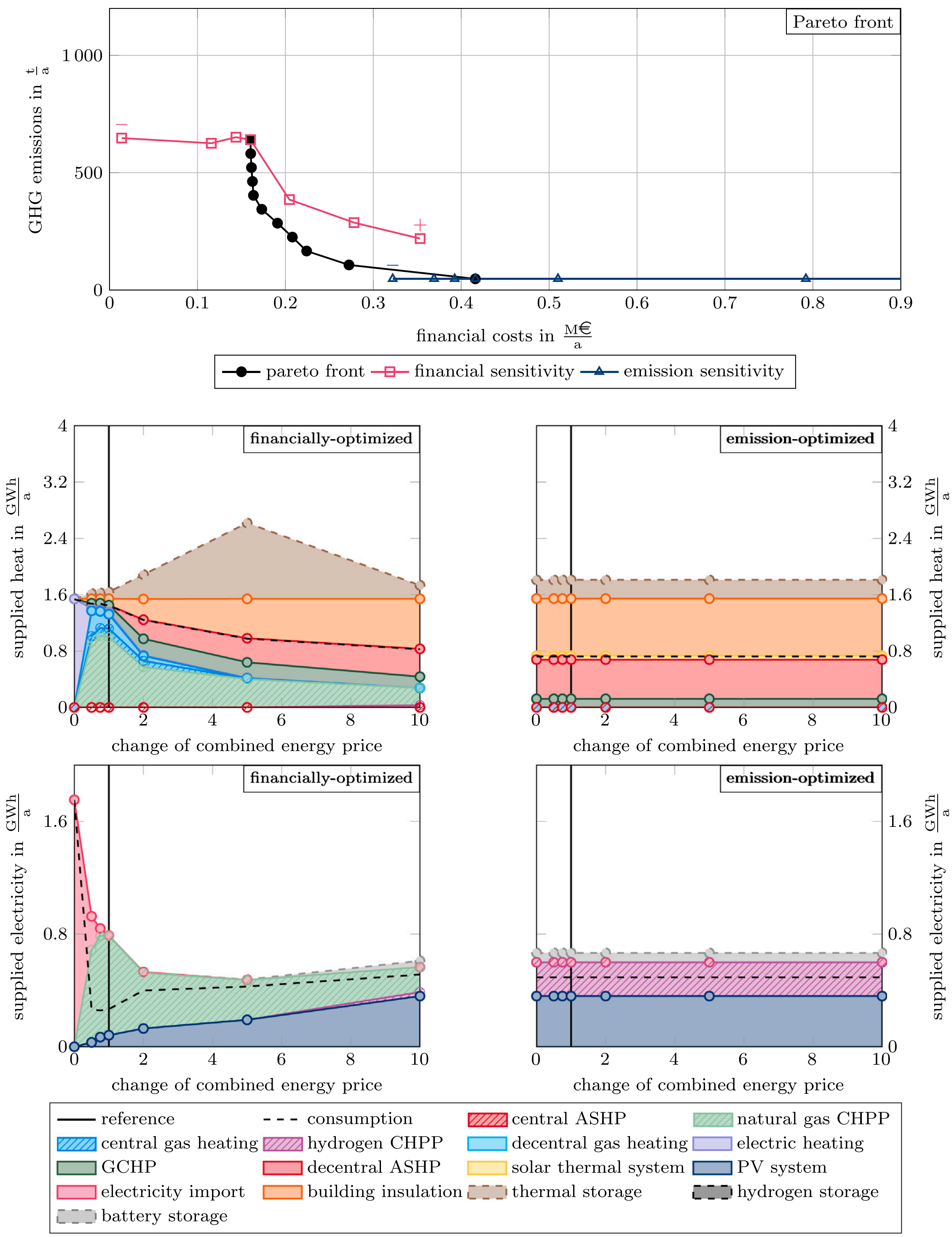

Fig. 12. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (combined energy price). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 8
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of combined energy prices. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydro-gen CHPP in kW	Electrol-ysis in kW	Metha-nation in kW	Solar thermal system in kW	Electric heating in kW	Decen-tral gas heating in kW	PV system in kW	Decen-tral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydro-gen storage in kW h	DH buildings
FO-0.0	0	0	0	0	0	0	0	539	0	0	0	0	340	0	0	0
FO-0.5	121	92	0	0	0	0	0	117	98	29	0	10	687	0	0	11
FO-0.75	129	130	0	0	0	0	0	87	73	60	0	15	728	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-2.0	69	100	0	0	0	0	0	31	59	114	58	51	758	0	0	5
FO-5.0	93	6	0	0	0	0	0	46	8	165	99	54	1138	12	0	4
FO-10.0	81	0	0	10	50	0	0	54	0	295	132	39	1303	175	438	4
EO-0.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-0.5	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-0.75	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-2.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-5.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-10.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix I. Results: Electricity demand

See Fig. 13 and Table 9.

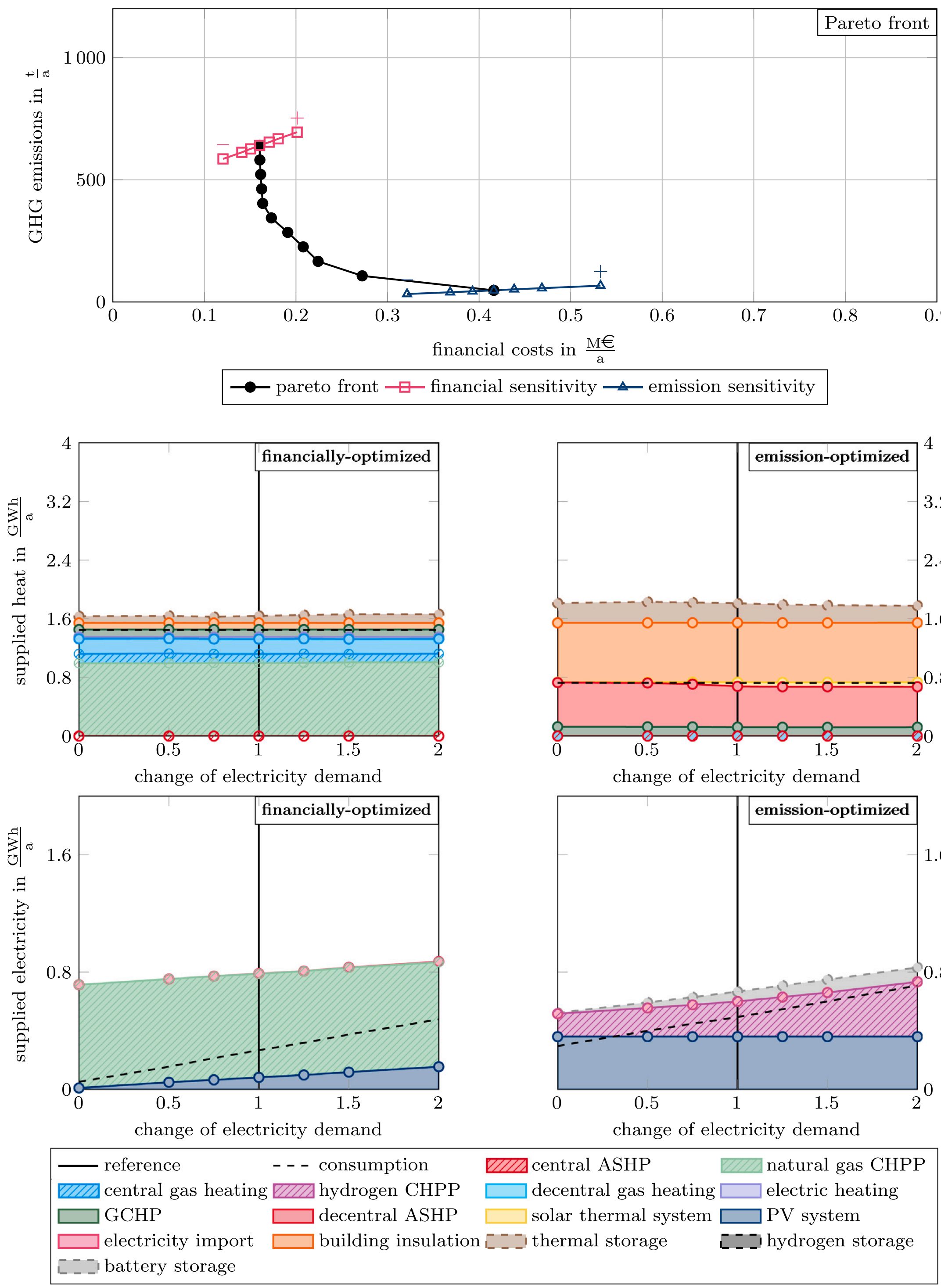

Fig. 13. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (electricity demand). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter. If the behavioral based electricity demand is reduced to zero the absolute electricity demand and thus the electricity supply has an offset, which is caused by the electrified heat supply.

Table 9
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of electricity demands. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydrogen CHPP in kW	Electrolysis in kW	Methanation in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydrogen storage in kW h	DH buildings
FO-0.0	124	114	0	0	0	0	0	111	65	8	0	17	633	0	0	13
FO-0.5	123	131	0	0	0	0	0	90	65	42	0	17	701	0	0	13
FO-0.75	125	110	0	0	0	0	0	113	65	56	0	17	635	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.25	125	119	0	0	0	0	0	102	65	84	0	17	649	0	0	13
FO-1.5	127	103	0	0	0	0	0	116	66	101	0	17	633	0	0	13
FO-2.0	127	117	0	0	0	0	0	97	65	132	0	18	720	0	0	13
EO-0.0	0	0	0	155	22	0	4	22	0	295	230	28	1422	36	22	0
EO-0.5	0	0	0	178	0	0	12	0	0	295	241	28	1592	172	0	0
EO-0.75	0	0	0	186	0	0	29	0	0	295	234	28	1658	263	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.25	0	0	0	185	0	0	62	0	0	295	202	28	1508	417	0	0
EO-1.5	0	0	0	191	11	0	62	11	0	295	194	28	1452	496	11	0
EO-2.0	0	0	0	209	33	0	63	33	0	295	187	28	1527	623	33	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix J. Results: Heat demand

See Fig. 14 and Table 10.

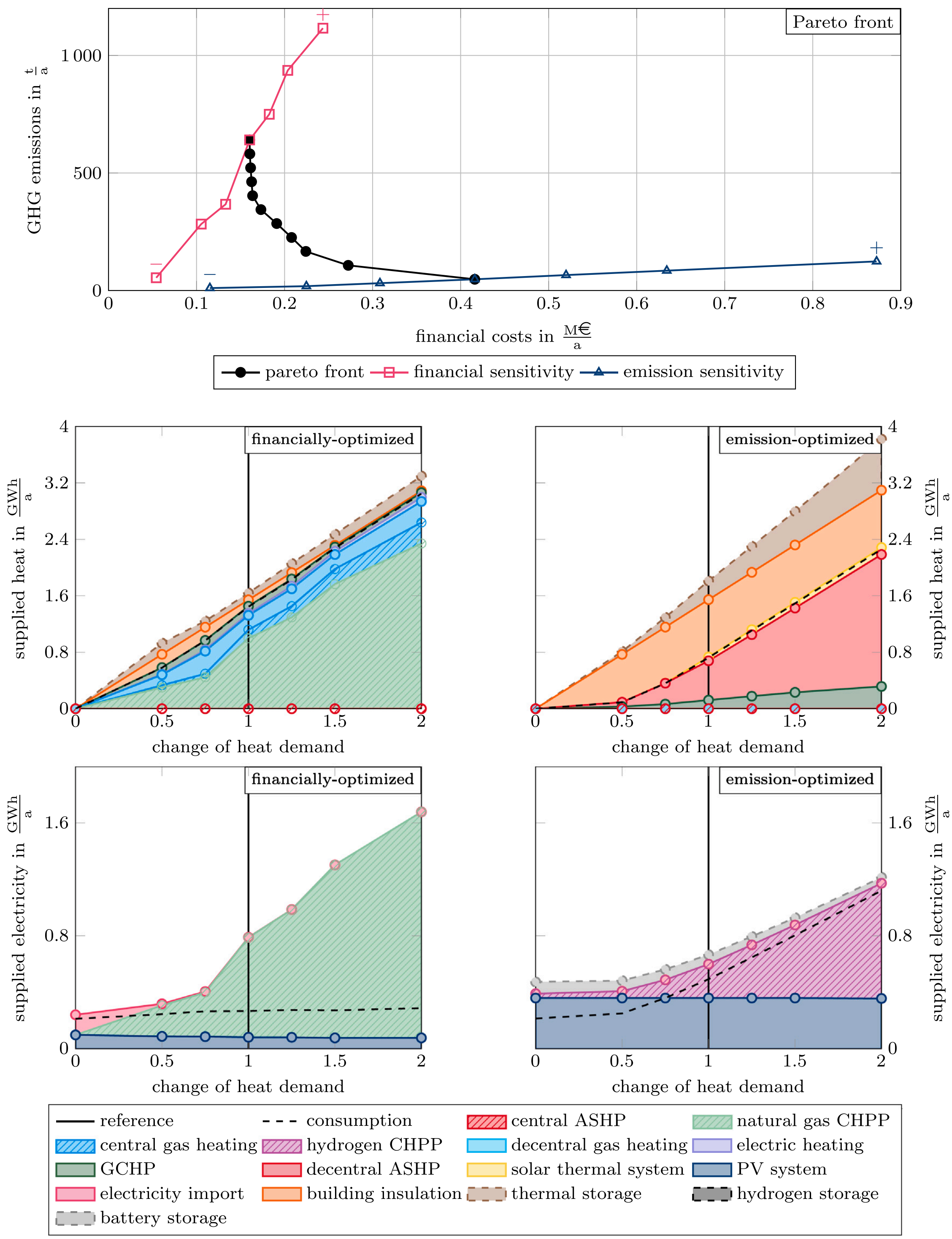

Fig. 14. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (heat demand). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 10
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of heat demands. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydrogen CHPP in kW	Electrolysis in kW	Methanation in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydrogen storage in kW h	DH buildings
FO-0.0	0	0	0	0	0	0	0	0	0	84	0	0	0	0	0	0
FO-0.5	39	44	0	0	0	0	0	22	49	75	0	18	314	0	0	5
FO-0.75	56	56	0	0	0	0	0	58	99	74	0	23	491	0	0	5
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.25	160	136	0	0	0	0	0	148	78	70	0	19	796	0	0	14
FO-1.5	218	182	0	0	0	0	0	187	66	66	0	9	975	0	0	16
FO-2.0	285	246	0	0	0	0	0	251	94	66	0	9	1304	0	0	16
EO-0.0	0	0	0	37	0	0	0	0	0	295	0	0	0	360	0	0
EO-0.5	0	0	0	57	26	0	0	26	0	295	51	5	292	332	26	0
EO-0.75	0	0	0	105	0	0	2	0	0	295	118	14	689	351	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.25	0	0	0	247	0	0	74	0	0	295	298	41	2074	323	0	0
EO-1.5	0	0	0	319	0	0	85	0	0	295	399	52	2623	311	0	0
EO-2.0	0	0	0	473	0	0	101	0	0	292	619	65	3797	304	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

Appendix K. Results: Population density

See Fig. 15 and Table 11.

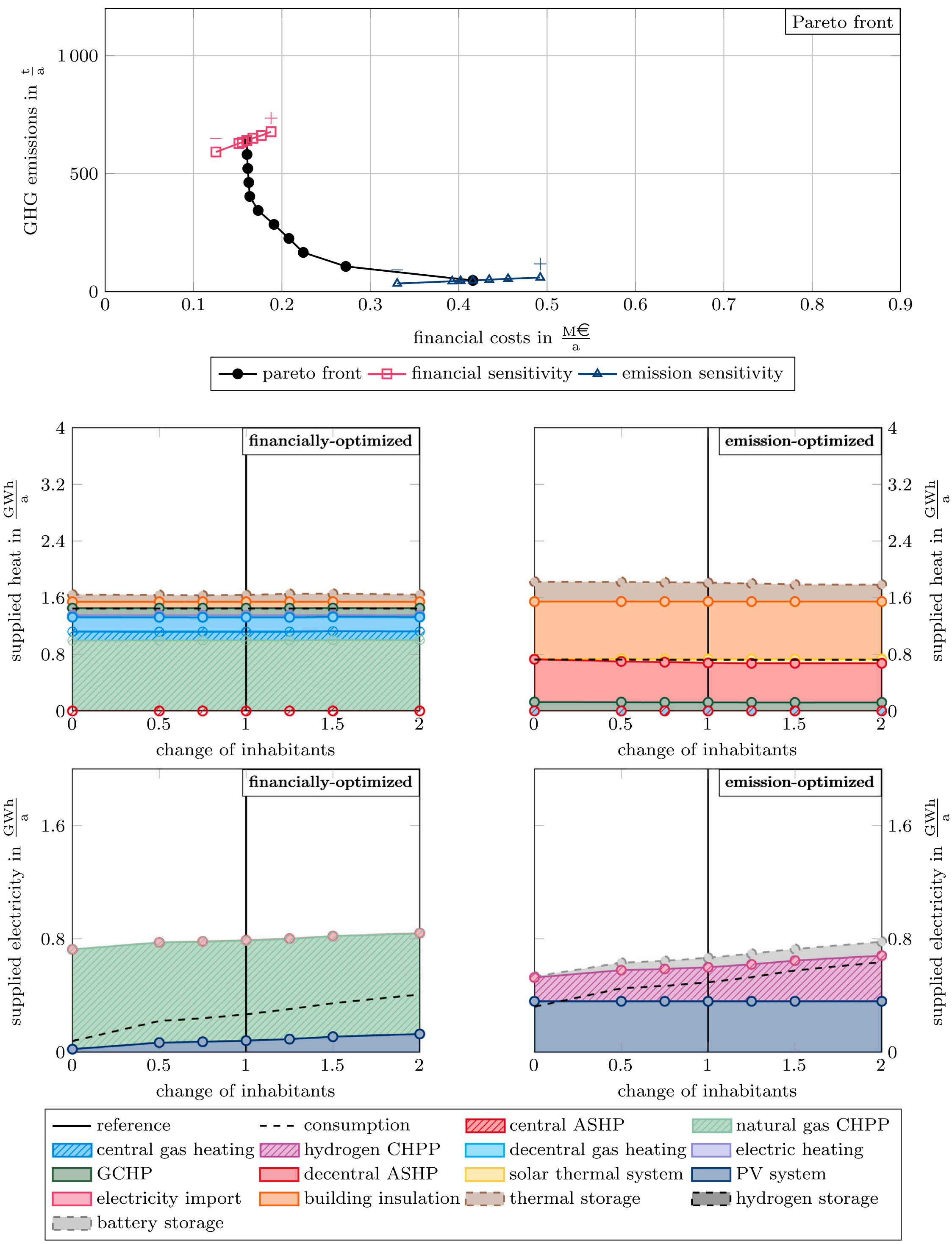

Fig. 15. Deviations financially-optimized and emission-optimized scenarios caused by changes of the sensitivity parameter (population density). Pareto front (top diagram): Changes of the financially-optimized scenario are shown in red of emission-optimized scenario in blue. If no changes occur, the points lie on top of each other. Otherwise, the lowest value (0% of the sensitivity parameter compared to the reference case) is marked as "−", the highest as "+ ". **Supplied energy (four diagrams below):** Supplied heat (top) and electricity (bottom) per inhabitant in the financially (left) and emission-optimized (right) reference case in dependency on the sensitivity parameter.

Table 11
Optimized technology capacities in the financially-optimized (FO) and emission-optimized (EO) reference case in dependency on changes of population density. The results are aggregated for each technology type.

Scenario	Natural gas CHPP in kW	Central gas heating in kW	Central ASHP in kW	Hydro-gen CHPP in kW	Electroly-sis in kW	Methana-tion in kW	Solar thermal system in kW	Electric heating in kW	Decentral gas heating in kW	PV system in kW	Decentral ASHP in kW	GCHP in kW	Thermal storage in kW h	Battery storage in kW h	Hydro-gen storage in kW h	DH buildings
FO-0.0	124	112	0	0	0	0	0	113	65	17	0	17	631	0	0	13
FO-0.5	125	106	0	0	0	0	0	117	66	57	0	17	628	0	0	13
FO-0.75	125	106	0	0	0	0	0	116	65	63	0	17	632	0	0	13
FO-1.0	125	106	0	0	0	0	0	116	65	70	0	17	632	0	0	13
FO-1.25	125	106	0	0	0	0	0	116	66	80	0	17	632	0	0	13
FO-1.5	125	128	0	0	0	0	0	90	65	95	0	18	699	0	0	13
FO-2.0	126	119	0	0	0	0	0	101	65	112	0	17	665	0	0	13
EO-0.0	0	0	0	165	4	0	4	4	0	295	239	28	1521	38	4	0
EO-0.5	0	0	0	182	0	0	38	0	0	295	228	28	1721	263	0	0
EO-0.75	0	0	0	184	0	0	45	0	0	295	225	28	1654	293	0	0
EO-1.0	0	0	0	185	0	0	56	0	0	295	218	28	1654	349	0	0
EO-1.25	0	0	0	186	16	0	62	16	0	295	208	28	1555	400	16	0
EO-1.5	0	0	0	187	0	0	61	0	0	295	194	28	1435	445	0	0
EO-2.0	0	0	0	203	0	0	62	0	0	295	194	28	1426	568	0	0

Acronyms: ASHP = air source heat pump; centr. = central; CHPP = combined heat and power plant; decentr. = decentral; DH = district heating; EO = emission-optimized; FO = financially-optimized; GCHP = ground coupled heat pump.

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