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Demystifying natural gas distribution grid decommissioning: An open-source approach to local deep decarbonization of urban neighborhoods

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ABSTRACT

In this paper, deep decarbonization in an urban neighborhood in Vienna, Austria is proposed focusing on decommissioning of the gas distribution grid for heat supply rather than trying to feed in "green" gas in the future. The core objective is to demonstrate that alternative network infrastructures and energy technologies ensure not only an adequate but also an even superior provision of local heat energy services. Two different deep decarbonization pathways are studied, namely, electrification of almost all energy services and expansion of the district heating network. In addition, future district cooling service supply is considered. The method applied couples and extends two open-source models offering a complete analysis toolkit covering a high spatial and temporal resolution. The results show that deep decarbonization of local multiple-energy carrier systems is possible, without being dependent on the existing distribution grid of natural gas. Possible stranded assets (also at the gas end-user level) must not play a decisive role, especially since the trade-off analyses in this work show that alternative scenarios of lower/zero-emission energy service provision are even more economical in the longer term since the CO_2 price is expected to increase in the next decades. Future work may focus, among others, on the energy generation technology mix feeding into the district heating grid, the local mobility service needs, and a higher granularity to improve the assessment of the on-site (building-integrated) renewable generation potential associated with the emergence of energy community concepts.

1. Introduction

A multitude of challenges related to ambitious global climate targets (e.g., the Paris Agreement [1]) and regional climate neutrality initiatives (e.g., the European Green Deal [2]) call for significant efforts in existing energy systems [3]. The challenges are subjected to climate change mitigation and expect fundamental changes in energy supply toward sustainability. This calls, in particular, for novelties in the provision of energy services, its efficiency, and energy demand reduction in general [4]. From an energy system perspective, deep decarbonization is an essential bit to the puzzle of a net-zero emission society and is associated with high shares of renewable energy resources and technologies [5].

In recent years, policymakers have pushed the exploitation of renewable energy resources and, in particular, corresponding energy technologies (e.g., wind, solar PV, and others [6]), which led to renewable energy generation and its facilities no longer being niche applications. On the contrary, massive market penetration and corresponding technological learning of these technologies have already achieved significant cost reduction [7]. Moreover, major renewable energy deployment and economies of scale contribute to successful transitioning from existing business models (which to a large extent is based on inefficient but cheap consumption of fossil fuels) toward sustainable ones [8]. The concerns associated with missing renewable energy profitability and economic viability by switching business models are continuously diminishing by techno-economic analyses (e.g., in Ref. [9]). They rather present the associated benefits.

Recent energy technology innovations and corresponding standardization have enabled, in most energy sectors, an entire toolkit encompassing a range of sustainable technology alternatives. In this context, energy systems increasingly describe a delicate balance (and related trade-offs) among different energy technology supply options. In some cases, these considerations lead

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- at least during the transition phase - to the decision to continue repowering of conventional energy technologies and maintain known business cases (e.g., mainly life-time extension and occasional attempts to build new generation capacities of nuclear power plants as zero-emission options in the electricity sector to mitigate the threat of a missing generation gap in the transitioning toward renewable energy systems [10]). However, in almost all cases, backward-looking decision making turns out to be myopic. Moreover, the implementation of sustainable technology alternatives justifies the decommissioning of (parts of) existing infrastructure of fossil energy carriers if not needed any more. This can also be seen as an opportunity for demystifying emerging sustainable and high-efficient energy supply alternatives.

The scope of this work aims at demystifying the undisputed dominant position of natural gas in the provision of heat services. This also includes the implicit assumption that “green” gas can be the one-fits-all solution for replacing “fossil” gas in a sustainable energy world.[1] This is not least because it is expected to be difficult that the quantities of green gas needed for all energy services and sectors will be economically available in the next few decades. However, it is undisputed that certain shares of green gas, and notably hydrogen, will be used in the future to supply higher-priority energy service needs in the transport and industry sector as well as in the energy sector for co-firing cogeneration power plants (e.g., feeding into district heating grids). However, at present, the economic viability of green gas and hydrogen production is still a big question mark. Production based on excess renewable electricity generation, a much cited argument in these days, is certainly not a sustainable business model in a competitive market environment. And finally, an admixture of hydrogen (if available) to green gas in the distribution grid is not yet fully clarified from the safety point-of-view either.

Against this background, the core objective of this work is to investigate the decommissioning of the local distribution grid of natural gas[2] in the heat supply of an urban neighborhood. This is also associated with a disconnection of the devices at the end-user's level, which are supplied directly with natural gas. In particular, the main research question is which alternative distribution grid capacities and sector coupling technologies are required to ensure an adequate, but sustainable development in the provision of local heat energy services (e.g., space heating and hot water). Two different local deep decarbonization pathways, namely, electrification of all energy services and an expansion of the district heating network, play a key role in the analysis. Within the scope, wide-range benefit indicators are introduced, enabling a comprehensive comparison toolkit and making associated trade-offs more apparent both qualitatively and quantitatively. Equally important is the consideration of the increasingly important cooling demand service needs within the neighborhood, which have received little attention to date. Nevertheless, the quantitative study of the (sustainable) energy mix feeding into the district heating network is outside the scope of this paper but included in future work.

The method applied extends and couples two verified open-source models, namely, *rivus* by Dorfner [11] and GUSTO [12]. The particular analysis focuses on the model *rivus*, which enables high-spatial resolved modeling exercises. Furthermore, this open-source model is expanded with further tailor-made functionalities (e.g., economies of scale and further energy services, such as cooling).[3] In addition, GUSTO analyzes local energy demand with a high temporal resolution and provides, in particular, the energy demand in the decarbonization pathways.

The numerical example analyzed is an urban neighborhood in Vienna, Austria. It is characterized by different building types and high diversity with respect to (i) load profiles, (ii) building structures, and (iii) occupancy intensity. Furthermore, emphasis is placed on the fact that the neighborhood is embedded in two underlaying districts and, therefore, takes into account potential synergies that stretch across system and administrative boundaries. Three different scenarios are carried out, covering (i) the current state of supply, (ii) a high electrification of local energy service provision, and (iii) a massive district heating and cooling network expansion.

The paper is organized as follows. Section 2 summarizes the state-of-the-art in literature and outlines the own contribution and novelties of this research. Section 3 presents the methodology, the set-up of the numerical example, as well as the investigated scenarios. Section 4 presents the results of this work for the three different scenarios. Finally, Section 5 discusses the results and concludes the work.

2. State-of-the-art and progress beyond

This section presents the most relevant scientific contributions related to this paper's scope. Hence, it addresses the following three main aspects: deep decarbonization pathways of energy systems on different scales (Section 2.1), distribution grid planning and energy infrastructure/facility decommissioning (Section 2.2), and trade-off analyses of energy technology portfolio implementation as well as associated benefit indicators in energy systems (Section 2.3). Finally, Section 2.4 outlines the own contributions and novelties of this work.

2.1. Deep decarbonization pathways of energy systems on different scales

In light of the energy system transition, deep decarbonization is of paramount importance and determines key priority challenges toward sustainable energy provision [13]. For this reason, many scientific contributions provide comprehensive studies dealing with (i) sustainable energy provision [14], (ii) efficiency-enhancements [15], and (iii) measures for energy demand reduction [16]. Generally, these studies carry out analyses with different emphases and on various scales (such as global, regional, or national levels [17]). The high-level goals are important cornerstones from an energy planning perspective and give guidance and future orientation. In this context, Loftus et al. [18] provide a critical review of global decarbonization scenarios covering several sectors. Victor et al. [19] as well as Brown and Botterud [20] conduct studies, in particular, for the decarbonization of the U.S. power sector. The trends of power system decarbonization in Europe [21], China [22], and other regions (see exemplarily in Ref. [23] by the authors Dranka and Ferreira) also head in a similar direction similar to those outlined in the U.S. studies. The decarbonization study in Ref. [24] by Auer et al. targeting climate neutrality in Europe in 2040 and 2050 is more comprehensive and covers several important sectors as there are energy, industry, building, and transport.

[1] The terminology “green” gas mainly describes biomethane and synthetic gases. It does not include hydrogen. If hydrogen is also meant, this is emphasized as extra.

[2] Low-pressure range in the gas distribution grid up to 6 bar.

[3] The authors are aware that open-source modeling is not per se a scientific contribution. However, this work is designated as another bit to emphasize open-source modeling and overcome black box analyses related to future energy system design.

Examples of in-depth analyses on decarbonization pathways in the transport sector and heavy industry can be found in Refs. [25,26], rspectively.

Furthermore, there exist already studies attempting to down-scale global/high-level studies to fine granulated structures or local levels [27]. Moreover, there is an increasing need for comprehensive down- and upscaling measures and tools, engaging the possibilities to map higher-level energy system goals on a local level [28]. For example, in the work by Chen et al. [29], it is identified that the implementation of aligned and sustainable energy planning is also important on the province, district, or neighborhood level. Consequently, comprehensive studies work on the disaggregation (or mapping) of superior/generalized decarbonization pathways on higher resolved spatial levels. The implementation of decarbonization pathways for whole cities is shown in Ref. [30] (and also in Ref. [31] focusing on investment needs on city levels). Leibowicz et al. [32] and Zhang et al. [33] decompose decarbonization pathways on an even higher resolution, such as on the building level. Thereby, the first study focuses on building thermal efficiency improvements, and the latter one, in particular, focuses on achieving the predefined national climate goals. Finally, it is important to note that spatial characteristics of the particular area need to be taken into account when developing the local decarbonization pathways. Different local areas or settlement patterns require different efforts. However, the scope of this work is densely populated and urban areas. It is referred to Zhao et al. [34], detecting a clear decarbonization trend in urban areas, accounting for the unique characteristics of highly populated neighborhoods.

2.2. Distribution grid planning and energy infrastructure decommissioning

Energy technology infrastructures are undergoing rapid changes. It is the consequence of various factors, such as the already mentioned ongoing decarbonization, but also decentralization, digitalization [35] and, ultimately "democratization" of the energy systems. Thus, in particular, energy distribution grid planning faces enormous challenges (i.e., incorporation of flexibility options [36], energy demand response [37], or providing the interface for charging high shares of electric vehicles [38]). In either case, distribution grid planning analyses require more than ever integrated/holistic approaches [39]. This includes, among others, sector coupling [40]. Since a large number of scientific contributions already comprehensively dealt with sector coupling, it is referred to the literature in this context (see Brown et al. [41], many further contributions, and additionally in the recently published review in Ref. [42] Ramsebner et al.).

In addition to energy network infrastructures and facilities, also innovations in the energy technology supply portfolio develop very fast (see Fleischhacker et al. [43] and especially related to energy storage deployment Ziegler et al. [44]). This is the main driver for the already partial phase-out and decommissioning of selected energy technologies and related infrastructures, respectively [45]. In particular, Fowler et al. [46] focu on decommissioning of natural gas infrastructure in the upstream energy sector. However, these actions led to profound changes and enabled the linkage and interaction of different energy technologies and carriers in energy systems. Considering this work's scope, the relevant study by Then et al. [47] analyzes interrelationships between distribution grids of different energy carriers as well as decisions of retrofitting measures of buildings in the context of final energy demand reduction. In this regard, the authors also explicitly want to cite Weidenaar et al. [48]. They develop options for the Dutch gas distribution grid in a changing natural gas market.

Complementing the scientific literature review above, the following paragraph should provide a few insights into the practical relevance of gas distribution grid decommissioning considerations. Thus, the real-world applicability of this work's study is visible. In this context, the Netherlands can be cited as a role model to discuss the future of gas without taboos. Although the Netherlands is considered as a European country with one of the highest natural gas reserves, they have committed themselves to consider a gas-free energy system in2050[4] that would fundamentally change the heat supply of new buildings and the existing building stock. This discussion also includes the related meaninglessness of green gas (but not of course, those of hydrogen to supply higher-priority energy services in other sectors). Moreover, individual cities in the Netherlands (e.g., Utrecht) have set even more ambitious targets and aim for a gas-free energy supply in2030.[5]

Furthermore, the city of Zürich in Switzerland with its 400 thousand inhabitants is pursuing a pioneering attempt.[6] The planned phase-out of the gas-based heat supply in the next years in two districts explicitly includes "stranded costs" considerations of end-user's gas supply infrastructure and appliances. Consequently, compensation payments for non-depreciated end-user investments associated with gas supply are granted.

This real-world example in Zürich is a first indication that in the energy transition, it is increasingly important to compare both the costs of removing "stranded assets" (including compensation payments to those who are affected) and the costs of inaction (including the costs of possible future penalties for failing to meet climate targets). Even more, business models and economic viability analyses in the energy transition must increasingly address these kinds of opportunity costs alongside the prices of energy carriers and its externalities. This casts already a different light on the attractiveness of gas-based business models both now and in the future.

2.3. Trade-offs in energy system planning and key performance indicators

A vast number of scientific contributions have already dealt with trade-off analyses in energy systems (see, e.g. Ref. [49]). In general, these kinds of analyses are caused by the fact that energy systems often have to meet different contradictory requirements [50]. The bandwidth of energy supply needs and objectives concerns, among others, techno-economic, security/reliability, and sustainability/environmental related goals. Therefore, energy system analyses accept the challenges to address multiple objectives [51]. This is achieved by integrated [52], holistic [53], and multi-criteria [54] energy planning approaches.

At the same time, further works depict that solutions optimized with respect to one specific objective are distant from each other keeping in mind the solutions of all possible objectives. Therefore, studies often analyze the so-called Pareto Front (describing a set of optimal solutions) [55]. For example, Fleischhacker et al. [43] show that the optimal cost-minimizing and emission-minimizing solutions lie on the extreme points of the Pareto Front. Therefore, it is likely that optimizing one objective leads to produce a suboptimal result related to another (compare, e.g., the ambivalence between

[4] https://www.oxfordenergy.org/publications/the-great-dutch-gas-transition/.

[5] https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Marktanalysen/2021/zma-niederlande-2021-energieeffizienz-gebaeude.html.

[6] https://www.ebp.ch/sites/default/files/2020-12/2019_EBP_Fachbericht_Zukunft_Gasinfrastruktur.pdf.

cost-optimal and security-optimal solutions [56]). Notwithstanding, in most energy system planning analyses predominantly cost-minimal solution has been mainly addressed so far (see, e.g. Ref. [57]).

Nevertheless, climate change related measures can no longer be placed behind the question of myopic economic viability considerations [58]. Hence, several works suggest that strategic energy system related decisions should strive to be subjected to the principle of sustainability and environmental-friendliness [59]. This takes into account binding agreements of climate and sustainable development goals [60] (see Bosetti et al. [61]). In addition, there are strong efforts to take increased account of still scarcely adopted cost components, such as externality and greenhouse gas emission costs.

In particular, long-term strategic decisions governing sustainable energy system transition require further benefit evaluation criteria. In scientific contributions and real-life applications, benefit/performance indicators enable a fundamentally enhanced assessment and supersede high-complex or rather academic multi-criteria analyses approaches. Afgan and da Graça Carvalho [62] conducted a fundamental work in the context of sustainability indicators for the assessment of energy systems. Vera and Langlois [63] as well as Kemmler and Spreng [64] are heading in a similar direction and conduct energy indicators for sustainable developments. Looking rather from a more general/global perspective, Reuter et al. [65] carry out a comprehensive indicator set for measuring energy efficiency benefits.

2.4. Progress beyond state-of-the-art

Building upon the abovementioned comprehensive literature review this work's contributions deliver novelties in this field of research beyond the state-of-the-art as follows:

- A deep decarbonization analysis of a multiple-energy carrier energy system of a local urban neighborhood is carried out by focusing on decommissioning of the natural gas distribution grid rather than trying to supply the gas grid with green gas in the future. Additionally, this is motivated by the energy policy decision to no longer allow natural gas connections for future new building areas. The demonstration of sustainable supply alternatives and thus the demystification of the necessity of sticking to the existing gas distribution grid is one of the main novelties of this work.
- The chosen case study of the spatially limited urban neighborhood clearly shows that high-level decarbonization goals are not something abstract or intangible, but can be implemented locally, taking into account several specific characteristics on-site. This includes mapping the local energy supply alternatives and network infrastructures as well as the building stock to enable detailed decarbonization scenario studies and assessment of its economic viability. Even more, a high-resolution local mapping also allows for quantification of possible synergies by achieving economies of scale and estimating the opportunity costs of alternative energy supply compared with inactivity (e.g., persisting with current natural gas distribution grid and end-user devices).
- The extension and application of the two open-source models can be seen as a significant contribution not only to the open-source scientific community but also to a wider public interested in transparent and comprehensive energy transition analyses tools. The functionality extension with regard to economies of scale in the modeling framework covers non-linearities describing not only the optimal local district heating/cooling expansion path but also implicitly the opportunity costs and penalties in light of unachievable climate targets as a result of inaction or inertia in the energy system transition.
- The introduced tailor-made benefit/performance indicators enhance benchmarking of the distinct local deep decarbonization pathways and make related energy system achievements and efforts measurable. Thus, it enables to monitor long-term sustainable or even net-zero emission energy supply pathways, such as those that are aimed at the climate target years 2040 and 2050. In particular, the introduced indicators serve to quantify the relative differences of the various energy system planning decisions of the respective decarbonization scenarios from a technical and economic perspective. Furthermore, the knowledge generated can be used for decision-making in the context of the local energy transition through the benefit indicators.

3. Methodology

In the following, the methodology of this work is presented. Hence, it is divided into three main parts. The coupled open-source models are described in Section 3.1. Then, a comprehensive set of benefit indicators is introduced in Section 3.2. Finally, the numerical example and scenarios are defined in Sections 3.3 and 3.4, respectively. The latter includes the current state of supply and the outline of two different technology portfolio options enabling local deep decarbonization.

3.1. Applied open-source models rivus and GUSTO

This work uses the two existing open-source models *rivus* [11] and *GUSTO* [12]. Consequently, the approach provides a framework that includes a complete analysis toolbox using the different/unique model strengths. Thereby, *rivus* facilitates the modeling of the (local) energy system with a high spatial resolution. In contrast, GUSTO's strength is modeling of local energy systems (i.e., small areas, such as neighborhoods or communities) with a high temporal resolution (e.g., hourly). Exploiting the models' differences and strengths in a single analysis framework that arises by the coupling approach provides a comprehensive toolset to answer this work's research question. The two open-source models used are already applied in different scientific contributions (e.g., in Ref. [43],[7] [12,66]). Therefore, the following sections highlight both models' most relevant aspects only (in the context of this work) and, in addition, explain the specific functionality extensions of *rivus* that are carried out in this work.

3.1.1. Existing open-source model rivus

The open-source model *rivus* is developed by Dorfner and published under the terms of the GNU General Public License. The model itself is well-documented, and the Python codebase is available on GitHub.[8] In the following, relevant aspects of the model are described. For a more detailed description, refer to the model's manual, the GitHub repository, and [11]. The model is a

[7] Note that a similar methodological concept has been provided in Ref. [43]. However, this study is not only a methodological and analytical extension of the latter reference according to the description of the own contribution and novelties in Section 2.4, but also the level of detail and granularity in this work, as well as the complexity and spatial extension of the test-bed in the urban neighborhood exceeds that one in Ref. [43] substantially.

[8] https://github.com/tum-ens/rivus.

mixed-integer linear program for cost-minimizing capacity planning of energy infrastructure networks. In general, different spatial scales of energy systems can be analyzed. In addition, the model allows to consider different energy carriers or commodities (e.g., electricity, natural gas, heating/cooling). The temporal resolution is represented by a few selected characteristic weighted time steps (i.e., base, high, peak).

The main model elements are (i) commodity sources, (ii) commodity transport connections (e.g., distribution lines), and (iii) commodity sinks. Hence, the optimal cost-minimizing solution ensures the satisfaction of the energy demand by using the available energy carrier supply and expansion of the transport connection capacities. Consequently, the essential model constraints address the limitation of the (nodal) commodity sources availability, the maximum transport connection capacity, and the (nodal) energy demand-supply satisfaction. The inputs of the model are technical and economic parameters (e.g., length-specific investment costs, specific capital costs, maximum transport line capacities, etc.) and high-resolved spatial data.[9] The outputs of the model are, among others, the commodity transport connection capacities.

3.1.2. Implementation of economies of scale

There are a variety of possibilities to consider economies of scale in energy systems. An example is the reduction of specific investment costs of energy technologies and infrastructure as a result of large-scale penetration as a result of technological "learning rates". This is not the approach adopted in this work. Instead, economies of scale of a massive district heating and cooling network expansion are considered from the perspective of opportunity costs and penalty payments due to CO_2 emissions.

In many cases, scientific contributions deal with the optimal expansion path and corresponding design of district heating networks[10] (see in Ref. [67]). In many instances, the existing district heating distribution grid design aims for supplying special heat consumers with a significant heat demand (see the purple line in Fig. 1a). Subsequently, further expansion stages can be realized: (Stage 0) connecting technically and economically feasible consumers to the existing infrastructure (e.g., heat consumers in the immediate proximity of the existing infrastructure) and (Stage 1/2/3) expanding the existing infrastructure to further connect those in addition to justify feasibility. Thereby, the different stages (1–3) distinguish by their heat density and consequently by their ratio of additional implemented line length and corresponding heat demand supplied in the case of connection[11] (see Fig. 1b).

In general, non-linearities along the optimal district heating grid expansion path (i.e., additional line lengths and capacities) and additional heat supply demand are indicated in the connection curve in Fig. 1b. The implication of this non-linear curve is taken into account in this work's objective function as follows: each point on the non-linear optimal expansion curve factors explicit (e.g., capital costs) and implicit costs. The latter are declared in this work as opportunity costs. These significantly depend (inversely) on the expansion scale of the district heating network (e.g., economies of scale) and consequently directly on the gas-based heat supply. Hence, the objective function is extended as follows:

$$\bar{c}\,osts = costs^{cap} + costs^{eos} \tag{1}$$

$costs^{cap}$ is the capital and investment costs (i.e., specific costs in EUR/MW and EUR/m), $costs^{eos}$ is the implicit opportunity costs as so-called economies of scale. These latter costs are defined as:

$$costs^{eos} = \sum_{\tau} \alpha_{\tau} \cdot \pi \cdot h \cdot r^{\tau} \cdot \Delta_{\tau}^{CO_2} \cdot p_{\tau}^{CO_2} \tag{2}$$

α_{τ} is the annuity present-value factor in 1/year, π is the natural gas connection capacity in MW, h is the full-load hours (or capacity factor) of the natural gas infrastructure in h, r is the renovation rate as a demand reduction factor in %, $\Delta_{\tau}^{CO_2}$ is the difference in specific emissions between natural gas and district heating, and $p_{\tau}^{CO_2}$ is the CO_2 price in EUR/t for each year τ. Hence, $costs^{eos}$ reflects CO_2 emission penalty payments due to gas-based heat supply and limited district heating energy supply (infrastructure expansion). The relation between natural gas connection capacity π and district heating expansion degree is the optimal district heating expansion path f in Equation 3

$$\pi = f\left(\sum_{i} \xi_{i}^{dh}\right) \tag{3}$$

$\xi_{i,s}^{dh}$ is the implemented line length of the district heating distribution grid at a specific line i. The modus operandi to determine f is as follows. In a first step, the optimization model calculates the optimal district heating expansion path taking into account discrete expansion stages. Hence, a single model calculation run includes limitation of the total district heating line length as follows

$$\sum_{i} \xi_{i}^{dh} \leq \xi_{s}^{dh,max} \tag{4}$$

$\xi_{s}^{dh,max}$ is the maximum district heating grid line length at expansion stage s. Simultaneously, the natural gas connection capacity can be calculated. Finally, this (non-linear) relation (Equation (3)) is implemented in the optimization framework as an input using the well-known SOS2 variables.[12] This approach highlights a perspective on large-scale energy distribution grid planning decisions (i.e., district heating and cooling network expansion) and its emission cost saving potentials. In particular, related potentials are even disaggregated on a human-scale and building level, respectively, in this work using tailor-made benefit indicators. Further details on these indicators can be found in Section 3.2.3.

3.1.3. Existing open-source model GUSTO

This section briefly explains the open-source model GUSTO. The model is a mixed-integer linear program and builds upon the existing open-source model *urbs*[13] by Dorfner [11]. Since the authors already published works using this model, it is referred to the references [12,66]. Therefore, it can be dealt with the most relevant aspects and highlights of the model in the following. GUSTO aims to optimize energy technology planning and technology dispatch on a local level taking into account a high temporal resolution. However,

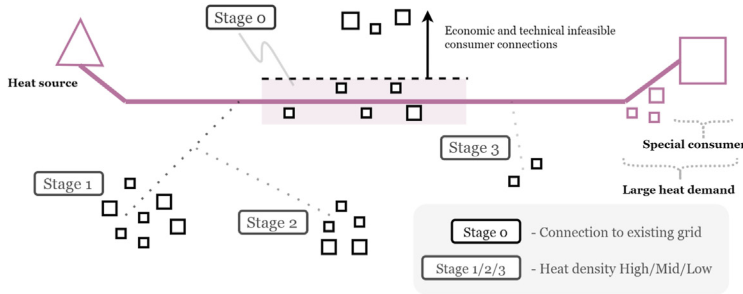
[9] This data is provided in shapefiles, and its handling requires considerable experience. The GitHub repository by Dorfner already provides some small case examples. Furthermore, all relevant files of this work are published in the authors' GitHub profile in a repository. Thus, the authors are committed to removing possible barriers in this context.

[10] Note that this applies to the same extent for the district cooling network. Therefore, it is sufficient to only address the district heating network in the following.

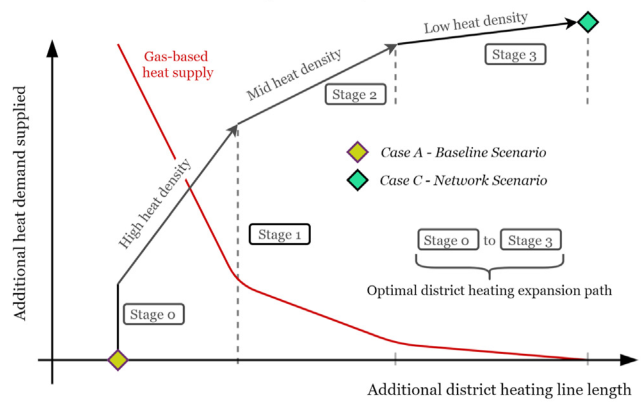
[11] Note that in this work *Case A - Baseline* represents the status quo, and *Case C - Network* represents the exhaustive optimal district heating grid infrastructure expansion within the feasible area. Both cases represent the corners of the analysis in this work. For a detailed scenario definition, it is referred to in Section 3.4.

[12] A specific binary decision variable set enables the linearization of non-linear relations between continuous model decision variables.

[13] https://github.com/tum-ens/urbs.



(a) Local area and its different district heating expansion paths (Stage 0-3) taking into account the existing infrastructure (magenta)



(b) Optimal district heating expansion path and corresponding gas-based heat supply considering different stages of expansion for varying heat density areas

Fig. 1. Indication of optimal district heating expansion paths on the basis of the existing infrastructure (a) and resulting non-linear relation between the district heating network and gas-based heat supply (b).

the model's spatial scope is, to some extent, limited. The tailor-made functionality expansion compared with the base model *urbs* provides a complete toolkit for low-level local energy system analyses (e.g., energy communities or local neighborhoods). In general, different objective functions can be considered. Among others, minimizing total costs of supply (i.e., investments and operation costs) and minimizing total greenhouse gas emissions are those with the highest practical applicability. In addition, the model allows taking into account the provision of different energy services (and commodity supply). The main constraints of the model's mathematical framework are the energy demand satisfaction of the (local) energy services (e.g., electricity, heating/cooling). In general, GUSTO includes also natural gas as an energy carrier (not needed here).

The role of GUSTO in this work's modeling framework. In this modeling framework, GUSTO's results are used as an input for the *rivus* model in the *High Electrification* decarbonization pathway (see Section 3.4). This scenario describes an (almost) complete electrification of the provision of local heating and cooling services within the neighborhood. The model coupling modus operandi is as follows. First, GUSTO calculates the optimal energy technology dispatch on the building level (different building types are carried out - see Appendix A). Note that the energy technology investment decision is determined by the corresponding decarbonization pathway (i.e., small-scale heat pumps for heat and compression machines for cooling supply). The high-temporal resolved results provide (i) peak demand and (ii) temporal distribution of the required/resulting electricity demand. Both characteristics are included in the *rivus* model's inputs. With respect to model coupling approaches, this can be denoted as so-called soft-coupling.

3.2. Definition of benefit indicators

This section provides the definition and description of this work's benefit indicators. They are founded on comprehensive literature research (see among others in Refs. [63,64] and also [68]). Moreover, the expansion of the tailor-made set of benefit indicators allows for a detailed benchmarking of small-scale local energy systems committed to deep decarbonization and sustainable energy supply. Four different benefit indicators dimensions are carried out.

Table 1
Description of capability and resource benefit indicators.

Indicator	Description	Unit
Waste	Waste incineration	None/Low/Mid/High
Geothermal	Large-scale	
On-site PV	Rooftop, building-integrated	
Heat pump	Small- and large-scale	
Green gas	Biomethane, synthetic gases	
Solarthermal	Rooftop	

3.2.1. Capability and resource benefit indicators

These qualitatively defined indicators address energy system benefits from a capability/resource perspective. This means that the different scenarios (or subsequently decarbonization pathways) enable wide-range resource utilization options. The corresponding benefit indicators (see Table 1) serve as a qualitative benchmark of their exploitation potentials. For example, *Waste* qualitatively addresses the integration/utilization potential for the provision of energy services using waste incineration (analogous to the remaining items in Table 1).

3.2.2. Technological benefit indicators

These quantitative indicators touch technological benefits from a practical implementation perspective (see Table 2). *Peaks* describes the network connection capacity expected to supply the neighborhood's energy services, and *Length* is the total distribution line length in the neighborhood. Note that both indicators take into account sector coupling and, therefore, include all energy carriers/commodities.

3.2.3. Economic benefit indicators

These quantitively defined economic indicators assess both cost and saving benefits in the different scenarios (see Table 3). Thereby, *Costs* describes the annualized technology cycle costs.[14] *Forex* indicates the cost savings per year by replacing natural gas in the energy service supply. In addition, *End-user* considers the average costs per building including (i) the capital and investment costs as well as (ii) the CO_2 price driven penalty payments as introduced in Section 3.1.2.

3.2.4. Sustainability benefit indicators

Finally, these quantitative indicators address relevant sustainability benefits and benchmark the deep decarbonization process and success in the urban neighborhood. Due to the self-explanatory (and intuitive) description in Table 4, a further detailed explanation is renounced.

3.3. Numerical example

In this work, a local natural gas distribution grid decommissioning and, consequently, natural gas phase-out in an urban neighborhood in Vienna, Austria, is proposed. This area is located in parts of two Viennese districts (2nd and 3rd districts) and describes a considerable spatial extension of the investigated energy community in the author's published work in Ref. [12]. The latter work focuses on a small fraction of this work's urban neighborhood with emphasis on demonstrating the local renewable energy sharing potentials inside the community.[15] In contrast, this work primarily deals with a high spatial analysis of distribution network capacities and implications resulting from an entire natural gas grid decommissioning in a much larger and more complex neighborhood. Hence, emphasis is placed on the spatial dispersion of the distribution grid capacity needs of a multiple-energy carrier energy system considering high shares of local renewable energy technology utilization.

In particular, this neighborhood is selected because it not only provides high diversity in (i) load profiles (electricity, heating, and cooling), (ii) building structures, and (iii) occupancy intensity but also describes a diverse representative urban area not only restricted to Austrian settlement patterns. Moreover, the characteristics of the test-bed include a residential area, public administration buildings, special consumers, a recreation area with selective energy service needs, a spatial separation by a river canal, cross-district administrative planning responsibilities, and more. For example, the heterogeneity and detailed description of the different building types and thus energy service needs can be found in Appendix A.

Two more aspects related to the distribution grid analysis are important in this work. First, the local natural gas phase-out concerns the low-pressure grid in the range of 3–6 bar.[16] Second, the electricity distribution grid capacities (in MW) considered neglect the detailed analysis of the different voltage levels ranging in Austria from 0.23 to 30 kV.

Table 2
Description of technological benefit indicators.

Indicator	Description	Unit
Peak	Peak public network connection capacity	MW
Length	Distribution line length	km

Table 3
Description of economic benefit indicators.

Indicator	Description	Unit
Costs	Annualized technology cycle costs	EUR/MWh
Forex	Annual natural gas forex savings	$/year
End-user	Average end-user energy and emission costs	EUR/building

Table 4
Description of sustainability benefit indicators.

Indicator	Description	Unit
CO_2	CO_2 tons saved per year	tCO_2/year
Fossil	Reduced fossil fuel consumption per year	MWh

3.4. Scenario definition

In the following, three scenarios (including the current state of supply and two different local deep decarbonization pathways) are described narratively. The scenario analysis shall bring further insights, among others, into the (i) sustainability degree of the current state of supply (Case A) and (ii) efforts as well as benefits from different perspectives in case of ambitious decarbonization of the energy service supply (Cases B and C). The narratives of the three different scenarios are based on dedicated “what if/how” questions. The two local deep decarbonization pathways (Cases B and C) focus on distinct structural changes in the energy distribution grid portfolio and, subsequently, technology supply options feeding into these grids.

Case A - Baseline (current state of supply)

This scenario builds upon the existing distribution grid in the urban neighborhood. It contributes to answer the question: what distribution grid capacities are available/required to supply the

[14] I.e., economic depreciation of technologies and infrastructures.

[15] The energy community in Ref. [12] is built by four different sites, namely two special consumers (i.e., football stadium and university), a residential area, and a new building area.

[16] As mentioned in the introduction section of this paper, co-firing of green gas in cogeneration plants as a fueling technology feeding into the district heating network is possible. However, this is not the focal point of this analysis.

current local energy demand. Note, at present, there is no comprehensive cooling demand service available in the area. The distribution grid includes mainly electricity and gas infrastructure. Furthermore, the special consumers within the area are connected to and supplied by the district heating network only (see also Figs. 2–4 in Section 4).

Case B - High electrification

This scenario considers high electrification of the energy service provision in the entire neighborhood subject to investigation. Consequently, the heat demand (previously mainly supplied by natural gas) is completely covered by electricity "fueled" technologies (i.e., small-/large-scale heat pumps). Note that the special consumers within the area are still supplied by the district heating network. Furthermore, this scenario takes into account an expected increasing local cooling demand, which is delivered by electricity-based technologies (i.e., compression cooling machines). Thereby, the integration of high shares of local renewable energy generation plays a crucial role (see related benefit indicators in Table 1). Synoptically, this scenario investigates a local decarbonization pathway of the urban neighborhood by an almost entire electrification of the energy service supply.

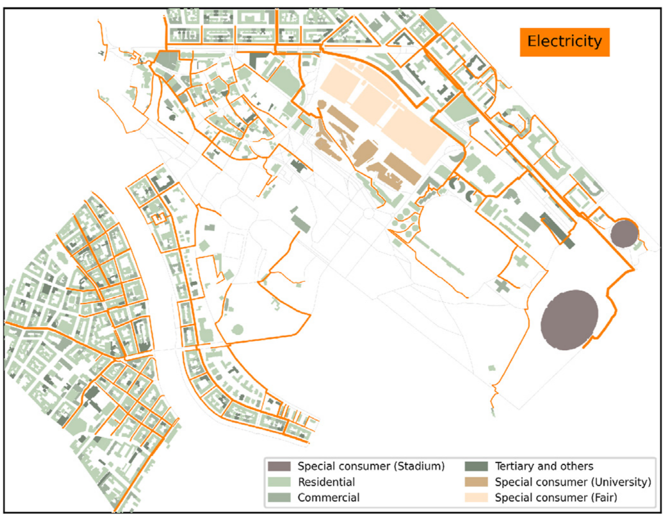


Fig. 2. Local electricity distribution network in *Case A - Baseline*.

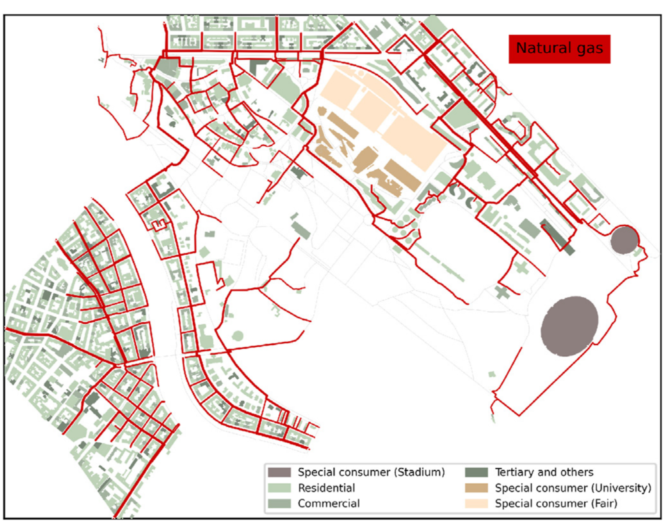


Fig. 3. Local natural gas distribution network in *Case A - Baseline*.

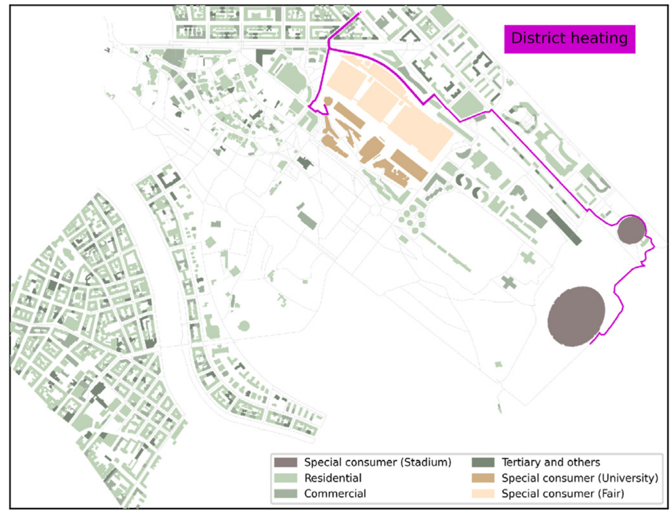


Fig. 4. Local district heating network in *Case A - Baseline*.

Case C - District heating/cooling network expansion

This scenario considers a large-scale district heating and cooling network expansion within the urban neighborhood. The local natural gas distribution grid/demand is replaced by the district heating network supply. In addition, the increased cooling demand is covered by the district cooling network. Furthermore, the electricity demand remains constant in comparison with the current state of supply. Note that this distribution grid focused scenario places no emphasis on the energy generation technologies feeding into the heating/cooling grid. The technology portfolio in the district heating/cooling generation mix does not directly influence the distribution grid capacities determined in this analysis. However, related generation technology specific aspects are discussed qualitatively in the results in the context of the different benefit indicator evaluations. Furthermore, this scenario considers a case study of the "non-discriminatory right" to be connected to the heating/cooling grid, regardless of the distance to the existing grid and heat/cold densities. The corresponding economies of scale of the socialized costs of this non-discriminatory grid connection are benchmarked according to the tailor-made benefit indicator definition in Table 3 (End-user) and presented in the related result in Section 4.4.

4. Results and discussion

This section presents, discusses, and compares the modeling results of three scenarios. Section 4.1 presents the current state of supply (*Case A - Baseline*). Sections 4.2 and 4.3 elaborate on *Case B -*

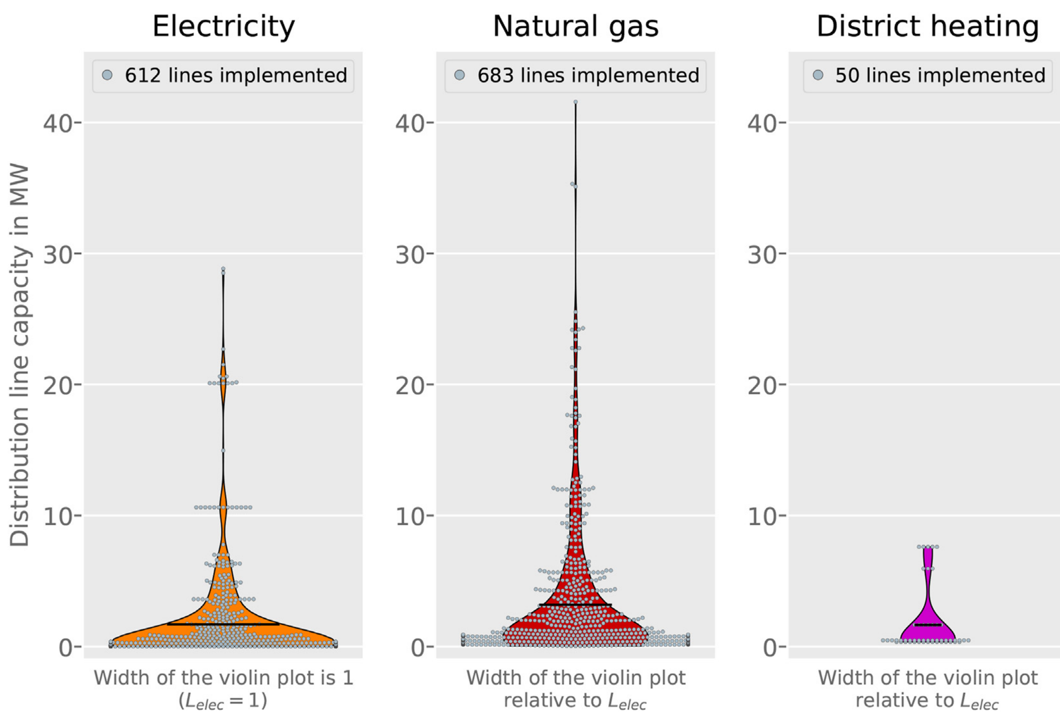


Fig. 5. Violin plot (incl. mean value indicated by the black bar) showing the distribution of line capacities within the neighborhood of electricity (left), natural gas (middle), and district heating (right) in *Case A - Baseline*. The widths of the violin plots are proportional to the number of implemented lines (gray points) and relative to each other. The width of the violin plot of electricity (L_{elec}) is set to 1 as reference.

Electrification and *Case C - Network*, respectively. Section 4.4 shows the end-user benefits in *Case C* as a result of the economies of scale achieved. Finally, Section 4.5 compares the three scenario results through application of the benefit indicators.

4.1. Case A - Baseline

At present, high shares of the local energy demand are supplied by the electricity (Fig. 2) and natural gas distribution grid (Fig. 3). The mean electricity line capacity in the test-bed is 1.34 MW, and the maximum is 28.48 MW. The largest electricity line capacities serve as a grid connection capacity to the public grid and supply the three special consumers (*Stadium*, *University*, and *Fair*).

The natural gas distribution network supplies almost the entire heat demand in the neighborhood. In addition, the district heating network supplies heat demand of the three special consumer in the district (Fig. 4). The maximum district heating line capacity is 7.61 MW. Note that *Case A* neglects cooling services because currently no district cooling network is implemented.

Fig. 5 shows the distribution of line capacitiesfor electricity, natural gas, and district heating using the so-called *violin plot*. For comparibility, the width of the violin plots are relativ to the each other, where the one of electricity is set to 1. The wider the violin plot, the more lines (indicated with the gray points) are implemented in this capacity range. The horizontal bars indicate the mean line capacity value for each energy carrier distribution network.Fig. 6 shows the total line length for the three energy carriers. Almost the same line lengths are required for electricity and natural gas, accounting for 96% of total local line lengths.Finally, Fig. 7 shows a binary heatmap for the networks of the three energy carriers electricity (top), natural gas (middle), and district heating (bottom). Each available distribution line is represented by a single element in the map. Note that the location of the elements is derived from the spatial setup in Figs. 2–4.

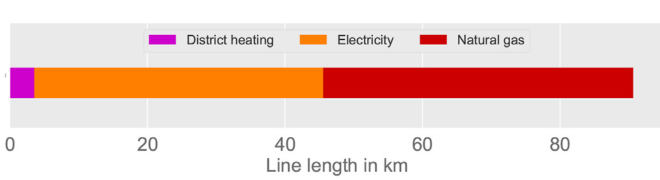


Fig. 6. Local distribution line length and its components in *Case A - Baseline*.

4.2. Case B - Electrification

In this scenario, the urban neighborhood pursues deep decarbonization by electrification of its energy supply. In addition, the natural gas phase-out in the heat supply, this scenario takes into account the cooling demand. The latter is mainly supplied by compression cooling machines. As a consequence, this further increases the local electricity demand. For example, the changes in the local energy system patterns are shown in Fig. 8a. It shows the annual electricity duration curve for a characteristic multi-apartment building in the neighborhood. Thereby, three different electrification levels are compared: (i) Baseline (*Case A - Baseline*), (ii) Heat (100%) considering the electrification of the heat demand only but neglecting the cooling demand, and (iii) a complete electrification (Heat and Cold (100%)). Fig. 8b compares the total energy demand in *Case A - Baseline* and in *Case B - Electrification* for the same multi-apartment building. Note that this section's further results take into account the electrification of both heating and cooling demand (indicated by the blue duration line in Fig. 8a). For the sake of clarity, a fully analogous result presentation similar to *Case A - Baseline* is omitted. Instead, Fig. 9 presents the distribution line capacities (again by the *violin plot*) for the local electricity (left) and district heating (right) distribution grid.

Again, the mean line capacity values are marked by the

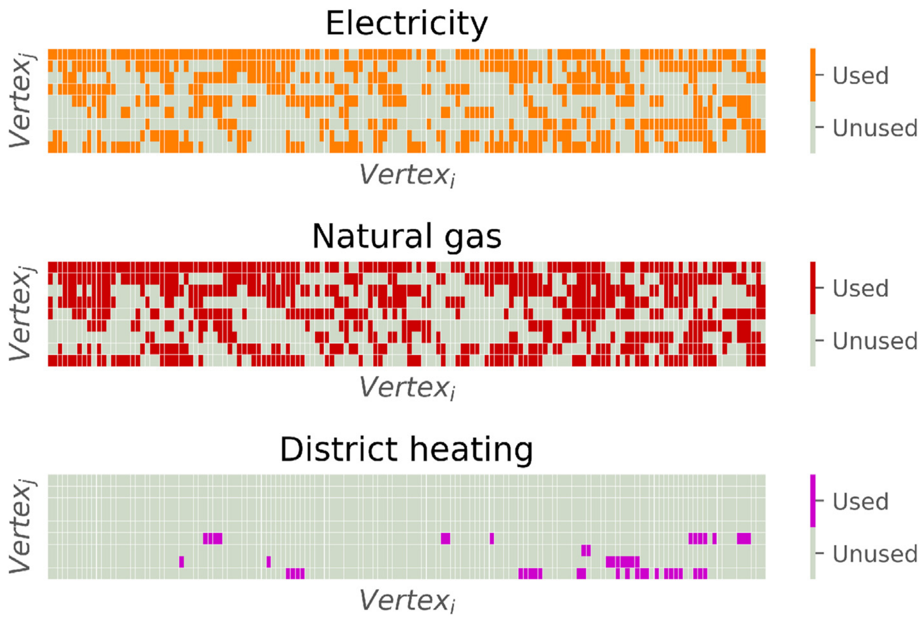
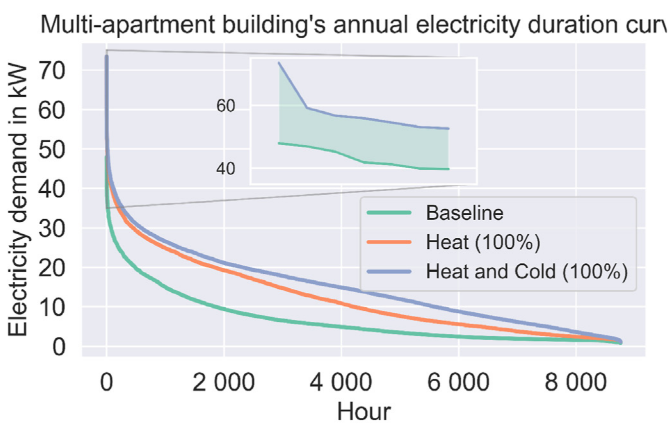
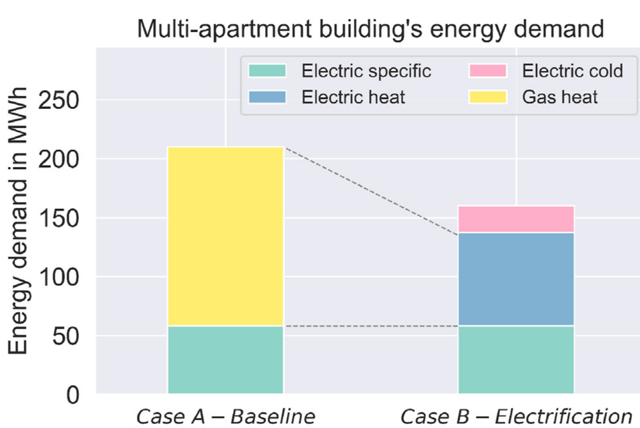


Fig. 7. Binary heatmap of the local distribution network for electricity (top), natural gas (middle), and district heating (bottom) in *Case A - Baseline*.



(a) Annual electricity duration curve



(b) Energy demand comparison

Fig. 8. Annual electricity duration curve (left) and comparison of total energy demand (including its components) for a characteristic multi-apartment building.

horizontal bars. In addition, the three figures in the middle of Fig. 9 highlight the differences of electricity line capacities between *Case A - Baseline* and *Case B - Electrification* (cutout of the line capacity frequency (top), max line capacity (middle), and mean line capacity (bottom)). Fig. 10 shows the resulting local distribution line lengths for electricity and district heating. The latter are unchanged compared to *Case A*. The electricity distribution line lengths are split into two parts, namely, the existing share of *Case A* (light orange) and the extra share of *Case B* (rich orange).

The extended (binary) heatmap in Fig. 11 shows the use of local available distribution lines for electricity (top) and district heating (bottom). For district heating the same results occur as in *Case A - Baseline* (Fig. 7) as the existing network still supplies the special consumers' heat demand. For electricity it mainly highlights the extra distribution lines demanded in *Case B - Electification* (rich orange) compared with those in *Case A - Baseline* (light orange).

4.3. Case C - Network

Fig. 12 shows the local distribution line capacities for district heating (left) and cooling (right). The district heating mean line capacity (top) and max line capacity compared with the *Case A - Baseline* is shown in the middle. It is evident that a significant increase for both is necessary to cover the heat demand. In addition, a massive expansion of the district cooling distribution grid is implemented, which is not existent in *Case A - Baseline*.

The massive district heating and cooling network expansion is also reflected by the extended heatmap in Fig. 13. The latter indicates a high level of available distribution line capacity utilization. Furthermore, it highlights available distribution line elements that are used for both district heating and cooling. The total distribution line length of the district heating network is 34.7 and 34.9 km of the district cooling network. Naturally, in this scenario, the corresponding indicator (*Costs*) in Table 3 is very high as a result of the scenario definition and the resulting massive network expansion. Nevertheless, it could be assumed that related results are too pessimistic (i.e., too costly) as possible synergies and related cost-savings from a simultaneous implementation of the district heating and district cooling network expansion are only considered to a

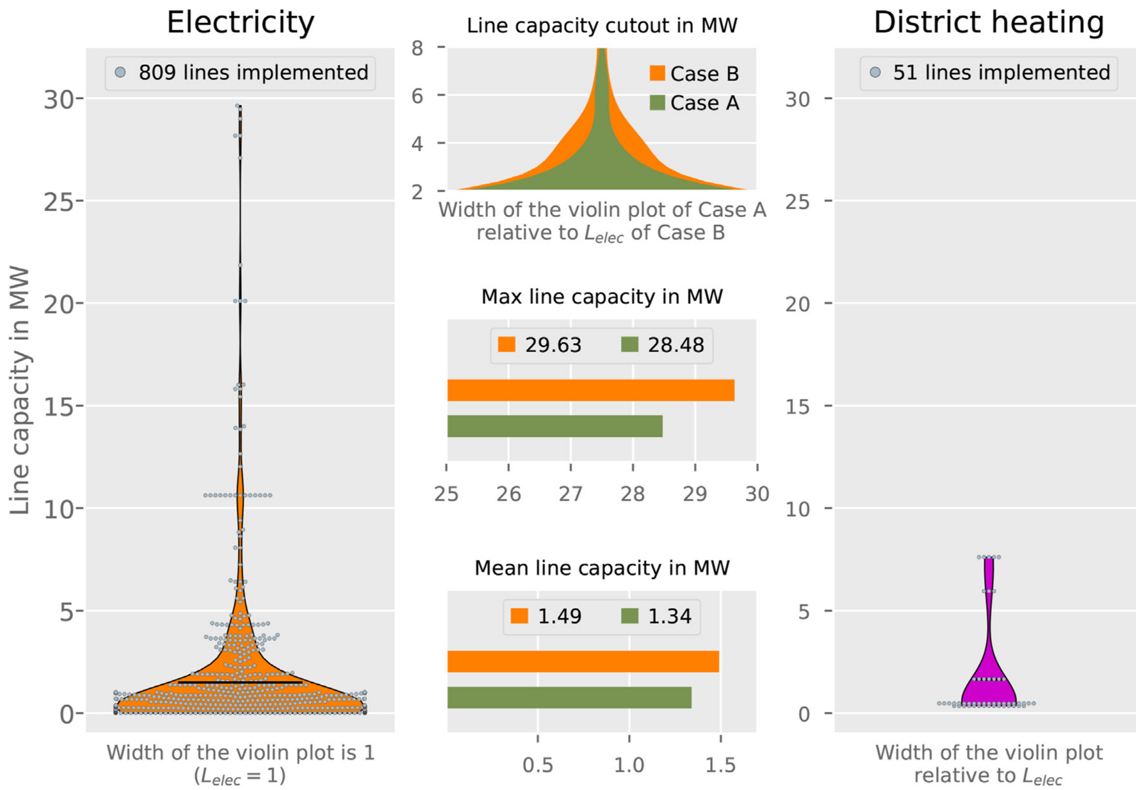


Fig. 9. Violin plot (incl. mean value indicated by the black bar) showing the distribution of line capacities within the neighborhood of electricity (left and district heating (right) in *Case A - Baseline*. The widths of the violin plots are proportional to the number of implemented lines (gray points) and relative to each other. Again, the width of the violin plot of electricity is set to 1. Selected highlights comparing electricity line capacities in *Case A - Baseline* and *Case B - Electrification*: cutout (top), max (middle), and mean (bottom).

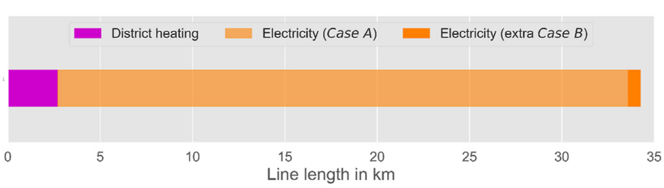


Fig. 10. Total line length and its components in *Case B - Electrification*.

limited extent. Thus, the following Section 4.4 considers the economies of scale of a district heating network expansion and related cost components exclusively. The latter are mapped on the building level to disclose end-user benefits in this sustainable local deep decarbonization pathway.

4.4. Economies of scale related to cost savings on an end-user level

The following analysis emphasizes the expansion of the district heating network on a large-scale in the entire supply area of the

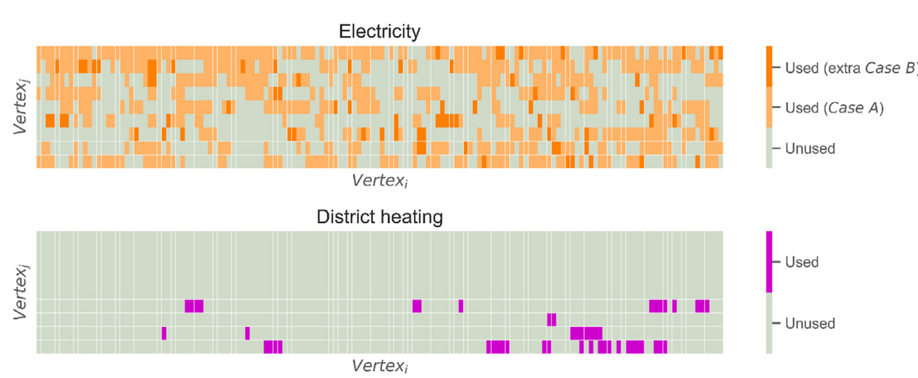


Fig. 11. Extended (binary) heatmap of the local distribution network for electricity (top) and district heating (bottom) in *Case B - Electrification*.

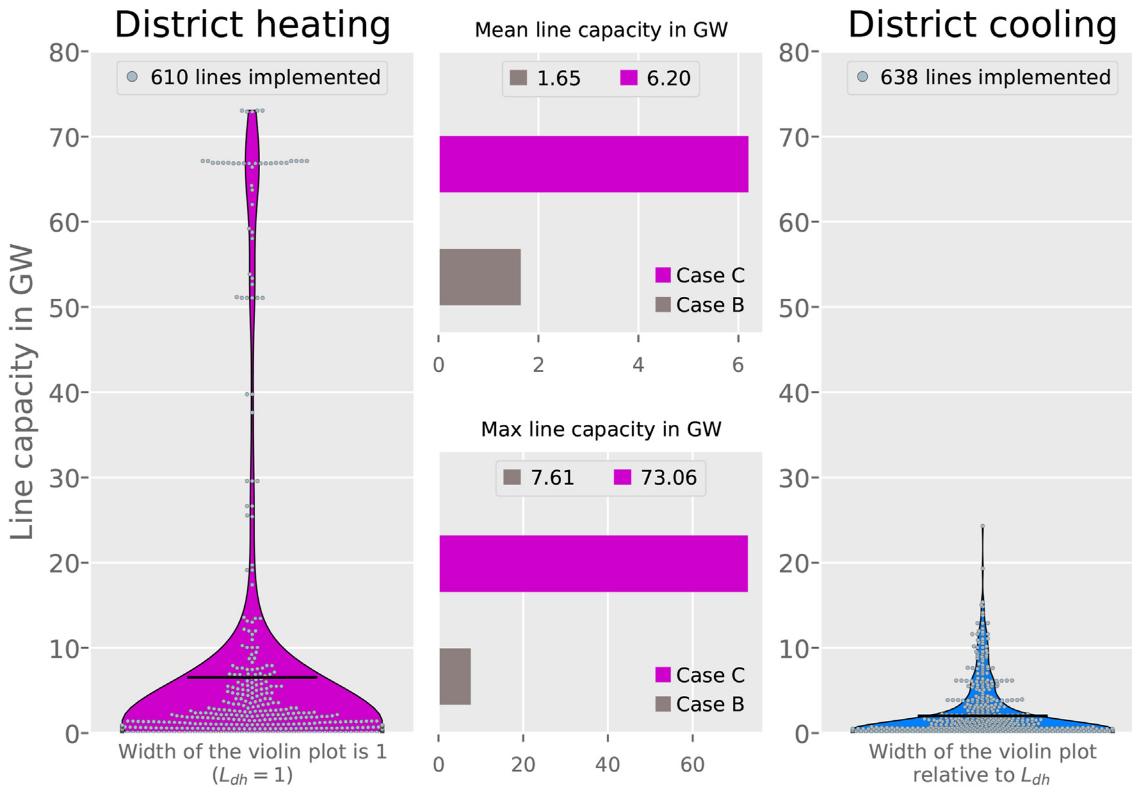


Fig. 12. Violin plot showing the distribution (incl. mean value) of line capacities of district heating (left) and district cooling (right) in *Case C*. The widths of the violin plots are relative to each other, where the width of the violin plot of district heating is set to 1 (again as reference). Implemented lines are again represented by the gray points. Selected highlights comparing *Case B* and *Case C*: mean (top) and max (bottom) of distribution line capacities.

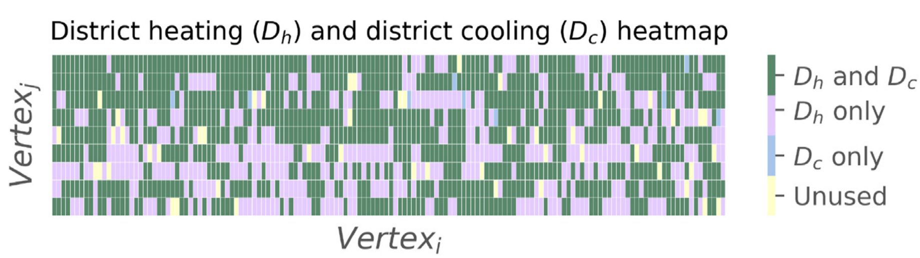


Fig. 13. Local district heating and cooling network heatmap in *Case C - Network*.

neighborhood according to the outlined scenario definition in Section 3.4. This includes the associated “non-discriminatory right” of the end-users to be connected to the grid (*Case C - Network*). In particular, the analyses emphasize the cost comparison between the current state of supply (*Case A - Baseline*) including its increasingly negative implications due to increasing CO_2 emission costs and the deep decarbonization pathway in *Case C - Network*. Fig. 14 compares the average building costs within the neighborhood in *Case A - Baseline* and *Case C - Network* for the heat demand supply taking into account a CO_2 price development[17] aiming for the European climate target for the period under review until 2050.

In addition, two different scenarios of the district heating energy generation mix are illustrated. The first scenario includes no further decarbonization in the district heating fueling energy mix and assumes that today's specific emissions remain constant until 2050. This assumption leads to average building cost parity between *Case A - Baseline* and *Case C - Network* in 2046 as indicated by the red diamond. Increasing decarbonization achievements of the district heating generation mix (i.e., stronger convex curvature of the solid black line *Case A - Baseline* as a result of halving district heating specific emissions from 2030) achieve earlier cost parity (green diamond in 2043). Moreover, the yellow marked area indicates the resulting total end-user cost-savings after the trade-off years. These cost-savings also increase with stronger convex curvature.

[17] This CO_2 price development is taken from the European Horizon 2020 project *openENTRANCE* (https://openentrance.eu/). As a main contribution of the project, both four different narrative storylines and corresponding quantitative scenarios have been developed. Thereby, three ambitious storylines/scenarios aim for the 1.5 °C climate target, the more conservative one (*Gradual Development*) for 2.0 °C. The corresponding endogenous CO_2 prices from the *Gradual Development* scenario are taken in this analysis. For more details, it is referred to Ref. [24].

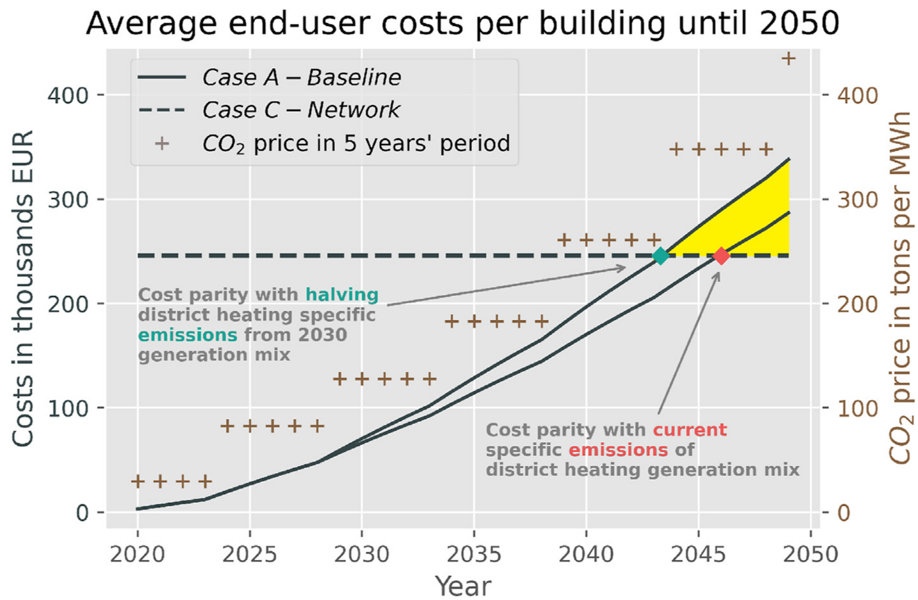


Fig. 14. End-user cost parity (on building level) comparing *Case A - Baseline* and *Case C - Network* with current district heating specific emissions (red diamond) and halving specific emissions from 2030 (green diamond). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

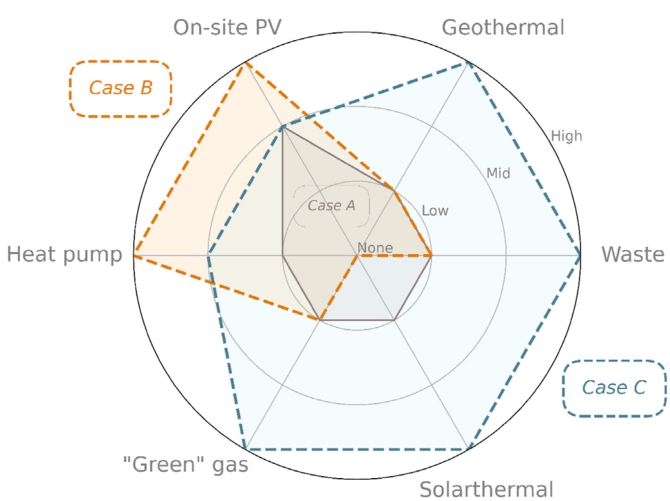


Fig. 15. Qualitative evaluation of capability benefit indicators including energy supply-side options in the three *Cases A, B and C.*

4.5. Result comparison with benefit indicators

Finally, this section conducts a results comparison using selected highlights of the introduced benefit indicators. Fig. 15 shows the capability and resource benefit indicator results.

They qualitatively assess the energy supply-side options in the different *Cases A, B, and C*. Note, that the analysis of the quantitative energy supply-side mix has not been the focus of this work. Thus, the discussion is qualitative in nature. Nevertheless, *Case A* (marked by the solid gray line) enables the integration of various distributed energy generation technologies, notably on-site PV systems for local electricity self-generation. In addition, limited integration potentials for geothermal, waste, solar thermal, green gas, and heat pumps exist. The main reason for this is the already existing heat supply of the special consumers within the neighborhood by the district heating network. *Case B - Electrification* may boost both technologies, on-site PV systems and small-scale heat pumps. As before, integration potentials for further technology/resource options are limited. In addition, the share of local PV self-consumption may significantly increase as a result of the electrification of the cooling supply. In *Case C - Network*, sustainable heat generation resources, such as geothermal, waste, solarthermal, green gas, and heat pumps, can be used to enable deep decarbonization in the heat supply. In particular, in the context of fueling cogeneration plants for feeding into the district heating grid green gas may deliver a significant contribution in this deep decarbonization pathway.

Fig. 16 shows further selected (and partly quantitative) benefit indicators related to the definition in Tables 1–4 (Section 3).

Thereby, in the two alternative decarbonization pathways both a significant reduction in CO_2 emissions and natural gas forex savings can be achieved. However, as indicated in both illustrations in Fig. 16a&b, the real-world application achievements of deep decarbonization in *Case B* and *Case C* may substantially depend on the energy supply-side mix. Furthermore, Fig. 16c compares the two decarbonization pathways with results from the status quo in *Case A*. The massive district heating and cooling network expansion in *Case C* results in significant increasing *costs* related to the distribution grid (see also the increasing total distribution line *length*). At the time, the increase in costs is significantly lower in *Case B*. Furthermore, the high-efficient electricity-based energy service supply in *Case B* leads to a significant reduction of the *Peak* (max) connection capacity in the neighborhood. In *Case C*, this capacity is almost constant compared with *Case A*.

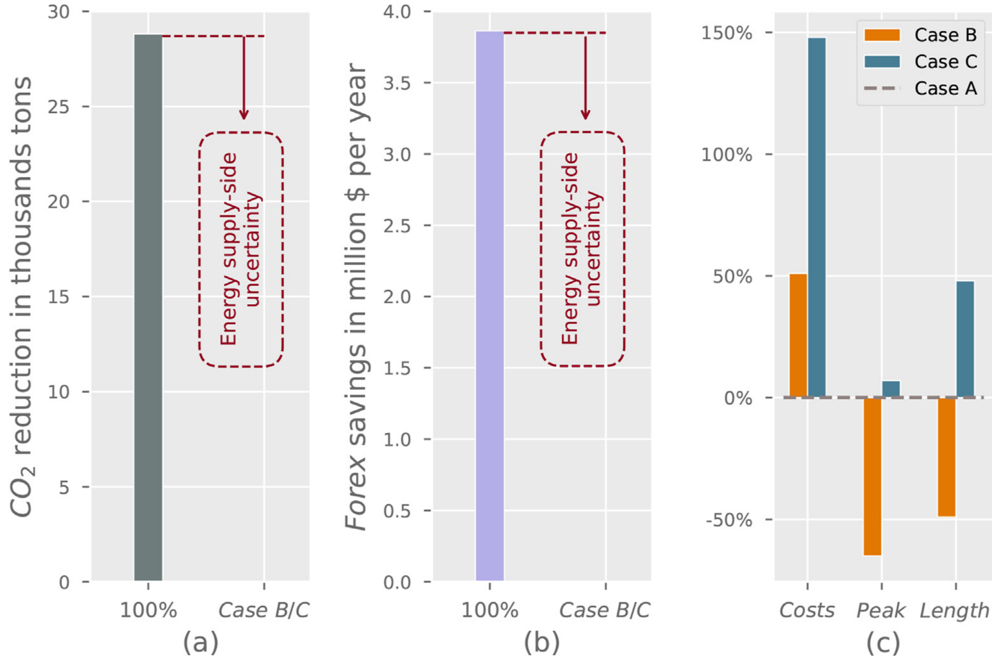


Fig. 16. Quantitative benefit indicators comparison between the three *Cases A,B and C*.

5. Conclusions and outlook

Building upon afeasibility case study in an urban neighborhood in Vienna, Austria, the analyses in this work not only have shown that deep decarbonization of a multiple-energy carrier system is possible, but this is also possible by decommissioning the local natural gas distribution grid. Against the background of the increasingly binding climate targets, it is very important to explore the full range of feasible options for sustainable local energy supply at the end-user's level off-limits, especially as the future potential and economic viability of green gas are uncertain at the end-user device level. Possible stranded assets must not play a decisive role, especially since the trade-off analyses in this work show that alternative network infrastructures and technologies of lower-emission or zero-emission energy service provision are even more economical in the medium to long term. Moreover, several methods, tools, and benefit indicators defined, developed and verified in this work have proven to be valuable to examine alternative technology options and network infrastructures for future energy service supply. This also includes the consideration of the increasingly important cooling service. The contributions of this work to further establish open-source modeling are straightforward, as leading edge science is committed to overcoming the black-box information asymmetries, to ensure the comprehensibility of analyses and to enable third parties to build on these models for carrying out their own tailor-made analyses.

Future work may focus, among others, on the following: (i) detailed analyses of the energy generation technology portfolio feeding into the district heating/cooling grid, focusing in particular on co-firing with green gas, geothermal sources, solarthermal, seasonal heat storage, and others, (ii) consideration of the mobility sector and its local energy service needs (public versus private mobility), and finally (iii) a higher granularity and spatial resolution of the building stock focusing on its efficiency, retrofitting measures, and implications of high shares of local (building-integrated) renewable generation in the context of energy community concepts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contribution

Sebastian Zwickl-Bernhard: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. Hans Auer: Conceptualization, Validation, Writing – review & editing, Supervision.

Appendix A. Detailed building description and empirical settings

The existing building stock within the urban neighborhood is split into different types and described in the following. Note that these building types can be easily adjusted or expanded according to the needs of further investigations.

Residential comprises different scales of multi-apartment buildings (e.g., small/large multi-apartment buildings). In this work, it is assumed that a characteristic residential building has four floors. The authors are aware that this assumption is to some extent a simplification. However, a more detailed consideration of the existing building stock composition (including its building quality/codes) can be part of further work (see this work's outlook).

Commercial includes the whole building stock used for commercial purposes (e.g., small industrial, retail, office, lodging, restaurant). *Tertiary and others* take into account buildings that are occupied by public authorities. Furthermore, it covers buildings such as shopping centers, hotels, and theaters. In addition, three different *Special consumers* complete the neighborhood's building stock (Stadium - *Ernst-Happel Stadium* and *Ferry-Dusika Stadium*, University - *Vienna University of Economics and Business*, and Fair - *Fair-Vienna*).

The empirical settings related to technical and economic assumptions are from Ref. [69]. These include the demand for energy services within the area. Note, that this work takes into account a continuous distribution line capacity available. Standard load profiles (hourly resolution) are used for the building types *Residential*, *Commercial*, and *Tertiary and others*. In particular, the electricity profiles are from Ref. [70], the heat profiles from Ref. [71] (see in this context also https://www.hotmaps.eu/) [72], and [73]. A recent study published by Priesmann et al. [74] provided additional information in the context of energy consumption patterns. The load profiles of special consumers are partly aggregated from data collections of previous projects [69] and partly from simulations or collected by estimations (see also the assumptions of the authors in Ref. [12] in the context of the demand assumptions for the special consumers.). Further empirical settings, in particular related to district heating and cooling economic parameters are used from Ref. [75]. Further technical and economic parameters of the grid are shown in Table A.1. The assumptions in the context of the CO_2 price between today and 2050 are shown in Table A.2. The values are obtained from the H2020 project openENTRANCE (https://openentrance.eu/). The initial connection costs for the characteristic multi-apartment building are assumed to be 350 EUR/kW on the basis of national empirical values from Ref. [69].

Table A.1
Technical and economic parameters of the grid. Sources [43]: and [76].

Grid	inv-cost	inv-cost-p	fix-cost	wacc	depreciation
	in EUR/m	in EUR/kW	in % of inv	in %	in a
Elec. grid	400	390	1	2	40
Heat. grid	500	742	1	2	40
Cold. grid	500	742	1	2	40

Table A.2
Development of the CO_2 price between 2025 and 2050. The *Gradual Development* scenario describes a future development where the 2.0 °C climate target is achieved. Values are taken from the H2020 project openENTRANCE. For further information see Ref. [24].

open entrance scenario	Time frame	CO_2 prices in EUR/t	Climate target in °C
Gradual Development	2025–2030	83–128	2.0 °C
	2030–2035	128–183	
	2035–2040	183–261	
	2040–2045	261–348	
	2045–2050	348–435	

Appendix B. Details of the optimization model

Table B.1 shows the description of the decision variables of the mixed-integer linear model. For further information (including the complete mathematical formulation of the equations), we refer to the official documentation of the open-source model *rivus* (see https://rivus.readthedocs.io/en/latest/) and the corresponding GitHub repository (https://github.com/tum-ens/rivus).

Table B.1
Detailed description of the decision variables of the mixed-integer linear program

Decision variable	Description	Type of variable	Bounds
c_{inv}	Total investment costs in EUR	Non-negative real	–
c_{fix}	Total annual fix costs in EUR	Non-negative real	–
c_{eos}	Total cost savings from economies-of-scale in EUR	Non-negative real	–
$P^{max}_{c,l,k}$	Line capacity of commodity c between node l and k in MW	Non-negative real	–
$q^{source}_{c,n}$	Connection capacity to the public grid of c at node n in MW	Non-negative real	–
$\sigma_{c,l,k}$	Supplied demand of c by line between l and k in MW	Non-negative real	–
$\xi_{c,l,k}$	Line implemented of c between l and k	Binary	0/1
l_c	Total line length of commodity c in meter	Non-negative real	–
$\psi_{c,l,k}$	Directional use of line of c between l and k	Binary	0/1

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