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Evaluation of future scenarios for gas distribution networks under hypothesis of decreasing heat demand in urban zones

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ABSTRACT

The consumption of buildings for the production of heat is expected to decrease in Switzerland in the coming years, in particular following policies encouraging the refurbishment of buildings. This will notably have an impact on the natural gas network, in parallel with the penetration of electric-driven heat pumps. Through a detailed optimization scheme, the evolution of the natural gas (NG) distribution network is studied over a future period of forty years, i.e. up to 2050, on the territory of a large Swiss canton. By way of installing large shares of co-generation units, it is shown that the NG network does not lose its meshed structure, while continuing to play a central role in the production of heat and the generation of part of the additional electricity demand associated with the concomitant penetration of heat pumps. As a novel result, the developed optimization framework allows a detailed, geographically precise view of both the evolution of the NG network, as well as of the optimal location of selected technologies. The adoption of energy networks convergence in urban zones therefore can lead to relevant synergies, avoiding over-investments, increasing system resilience and fostering the use of efficient technologies.

1. Introduction

Natural gas distribution networks play a fundamental energy supply role for cities all over the World, including the majority of European countries [1]. On one hand, natural gas is used for heating purposes by way of centralized or decentralized boilers and co-generation units, more rarely in gas-driven heat pumps, in many countries with an increasing share of renewable gases blended in (such as biogas from waste). On the other hand, NG is key to many industrial processes requiring high temperature levels, such as iron and steel production [2] and glass manufacturing. Such NG distribution networks have been implemented underground since the end of World War II and are still being densified or extended in many urban territories.

However, NG distribution grids are under pressure in some urban regions, mainly due to two concomitant dynamics [3]: i) the decrease of energy consumption per heated square meter due to energy efficiency measures adopted in many industrialized countries; ii) increasing obstacles to the usage of fossil NG as a result of climate policies, possibly leading to a future prohibition of installing gas-fired boilers in new dwellings and/or as part of residential heating systems refurbishments. Since NG distribution networks represent a capital-intensive infrastructure usually with very long amortisation times, the economical viability of the latter can be therefore be put in question by the two factors cited above and even lead to removal of pieces of the infrastructure. Such choices would clearly be detrimental to the development of future sustainable solutions based, e.g., on renewable gases and hydrogen.

On the contrary, in other regions, NG implementation for heating – and sometimes industrial - purposes is considered as a valuable alternative to coal- and oil-fired boilers, despite NG being a non-renewable energy vector, and is expected to bring short-term reductions of GHG emissions, i.e. playing the role of a „transition energy". Moreover, some European countries have put forward proactive policies favoring usage of both centralized and decentralized NG-based cogeneration units – in industrial as well as residential zones – in view of their high exergy efficiency and combination of both heat and power generation, particularly suited

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for Northern Emisphere countries, e.g. with cold continental climate features [4,5].

In view of these constraints and opportunities related to the usage of NG and implementation of CHP in urban zones, the research presented below tackles, as a central investigation question, the options for future evolution of a complete regional NG distribution grid. This novel perspective combines optimization, geospatial treatment of network and demand data on a real territory, network simulation tool and time-clustering approaches for future scenarios. To the best of our knowledge, such a thorough approach for a complete NG distribution network has not been applied yet at the level of a real urbanized territory, Indeed, the proposed analysis aims at studying the possible evolution of the NG network within a total wealth optimization procedure combined with a physical fluid mechanics grid model, while taking into account: i) the gradual decrease of energy demand for heating purposes at building level in both spatial and temporal dimensions; ii) the massive penetration of competing conversion technologies such as electricity-driven heat pumps, often considered as a globally environmentally-friendly option; iii) a possible future forbidding of both oil- and gas-fired boilers by way of a mandatory time limit for technology switch imposed by local authorities. Hence, the resulting indicators and detailed geographical, territorial distribution of technologies allow identifying optimized evolution paths for the NG distribution infrastructure, based on a set of manageable hypotheses both spatially and quantitatively. The results can be used for territorial energy planning by local authorities or utilities, in order to steer decisions in terms of grid maintenance, possible abandonment of certain grid branches or their valorization by proposing new usages such as NG filling stations for vehicles or by fostering hydrogen blending. Finally, our model includes residential co-generation units as one of the possible energy conversion technologies to be massively implemented in urban zones, leveraging on its high exergy efficiency. While the role of co-generation is already well established, e.g. in industry [6], a novel output of this study is highlighting the role of residential-level CHP units. In particular, their contribution is quantitatively put in perspective with respect to the penetration of power-driven heat pumps, whose supply will represent an important strain at the distribution low-voltage level, especially during winter, high-demand periods.

1.1. Literature review

This paper quantitatively addresses energy system planning of an extensive urban region by implementing a multi-level optimization model. Until now, optimization approaches only played minor part in industrial energy system and gas network planning, despite large number of academic studies showing the benefit of optimization in both fields. We divide the problematic into four parts and present the state of the art in each of them: (1) *Energy System Planning* (2) *Gas-Network Optimization* (3) *Heating System Optimization* and (4) *Combination of Gas Network and Heating System Optimization*.

Energy System Planning The design and management of energy supply infrastructures in urban areas represents a burgeoning research field in the last decade. This is related to the increased complexity of available technological solutions, evolving in parallel with local policies fostering energy efficiency in buildings, as well as penetration of solutions based on renewable energy sources. Hence, territorial energy planning approaches have been developed, based on decision-support strategies relying on interactive GIS platforms and smart data structuring (see e.g. Refs. [7,8]) or on optimization procedure aimed at identifying the most adequate technological supply energy conversion technologies [9], as well as networks configurations [10]. Extensive data collection and validation at building level granularity has been recognized as a key aspect to obtain a useful overview that can be implemented in concrete planning for local authorities and utilities. In particular, the importance of basing studies so far as possible on measured data is highlighted in many studies and is adopted in the present analysis.

Gas Network Optimization Indeed, a relatively small number of scholars deals with the topic of gas network optimization by optimizing the required power to operate the compressors. Both works [11], and [12], use a stationary gas demand to optimize the long distance gas transport network with compressors. The authors approximate the non-linear functions by predetermining solutions for each function.

In a recent paper [13], a full-scale optimization model of the national natural gas transport grid for the whole German territory is developed in order to evaluate various scenarios for the energy transition foreseen at political level (Energiewende): the crucial role of this network to attain the ambitious objectives set by the German Federal Government is clearly highlighted. In order to handle the great complexity of fluid transport networks [14], uses a graph decomposition based approach which is only valid for directed networks without cycles [15]. Apply a multi-period demand to design an optimal gas transmission network regarding the connections of pipeline and the sites of compressor stations, with consideration of terrains and obstacles. The non-linear pressure drop function is piece-wise linearized with a big M approach. In Ref. [16] also a multi-period optimization for a natural gas distribution network is presented. The model is able to design a new natural gas transmission network or even expanding an existing network by minimizing the overall investment and operating costs of the network. As a strong alternative to the transport of methane in gaseous form, LNG represents a quickly expanding path that is having a huge impact on this commodity sector, also in certain final usage sectors such as maritime transport. Advanced optimization techniques have been applied in the field of LNG, from both a process, as well as technology components point of view [17,18].

Heating System Optimization The problematic of optimizing heating systems is subject to many projects in recent decades. The usual approach is to design a new system, in that way every technology can be implemented initially [19]. Suggest an optimization approach for the heating system of the city of Zagreb with different heating technologies but also takes building refurbishment into account. They use a dynamic parameter variation over one year, in order to capture seasonality, and an hourly based time step for intra-day variations. The model demonstrated heating system based on renewable energy sources and district heating systems with highly efficient technologies have economic and environmental benefits. In Ref. [20] an mixed-integer linear programming for a single building based heating system is presented. The author focuses thereby on a great variation of sets of technologies, strategies and heat demand vectors. The consideration of a small case study, allow a very detailed and exact analysis of the system [21]. Uses a MILP approach, based on a superstructure with co-generation combustion units, conventional boilers, and also heat and cooling pumps to fulfil both heating and cooling demand for a set of buildings. The study addresses the problem of non-linearity of the part load efficiency for all heating units and economy of scale for the equipment investments, by piecewise linearization. The paper [22] focuses on an optimization model to determine the capability of district heating networks for large scale heating system with thermal storage over a one-year time horizon. While taking different heating technologies into account, the model optimizes the operation and capacity of the district heating network based on the interaction with the other systems. It must be noted that optimization frameworks have been applied in the field of industrial implementation of CHP and CCHP systems, providing interesting solutions to substantially increase energy efficiency in the production sector [2,6].

Combination of Gas Network and Energy System Optimisation In Ref. [23] a CHP based energy system with a district heating network is evaluated based on multi-period heat demand, by minimizing the overall costs for heat and power [24]. Optimizes the operation of a stationary high pressure gas network with compressors, in order to maximize the power of connected combined heat and power plants.

[25] optimizes the heating system on cities with around 200,000 inhabitants with CHP of small to large scale, with a connection of gas transportation pipelines. The study shows, the restriction of CHP technologies could increase the total system cost by around 2% and energy-efficiency by to 24% in comparison to the business-*as*-usual scenarios.

[26] divides the heating system of the United Kingdom and set a superstructure of a great variation of technologies and energy vectors, which need to be adapted separately, for each subset of the network. The subsets are connected with its neighbour subset through by the long distance energy vector transporting network.

2. Network and gas optimization model

In an energy system different stakeholders interact with each other, with often implicitly conflicting targets. On one hand, the utility providers seeks to maximize their profit margin while, on the other hand, the customers are interested in a cost efficient way to cover their heat demands. In this paper, we optimize a regional energy system as if all system internal members play together, i.e. in a total welfare approach. In reality, the customers do not consider the costs of future pipelines in their decision process as to choosing one heating option. However, the utility providers would pass these costs on all their grid customers by way of connection fees. Hence, there is an indirect link between both stakeholders, which justifies a global costs objective function in our optimization. All decisions in the model are only based on the considered time horizon (e.g. the next 40 years). Investments which would not be amortized over the selected timespan are not considered any more, since their usage is also not taken into account.

The considered natural gas network is subject to logistical and physical principles which needs to be valid at every considered time step. The optimization algorithm takes the $0, 1$ state of the gas pipelines and three heating technologies as decision variables into account: (1) conventional gas boilers, (2) heat pumps and (3) co-generation units with gas combustion. Other technologies are not directly included in the optimization, but are either considered beforehand in the data prepossessing or afterwards in form of new buildings. We assume that heating technologies operating on oil or wood will be replaced once the units are amortized. Existing buildings having already installed more sustainable conversion technologies (e.g. heat pumps) and new buildings with no pre-installed technologies are expected not to rely on natural gas combustion. The heating system is optimized over the Geneva cantonal territory, as described above, with a granularity chosen at single building level and based on the three selected technologies. In this framework, heat demand capacities are getting free each year due to the amortisation – and thus replacement - of oil, wood or natural gas boilers.

2.1. Definition of indices

In the following optimization model to facilitate the presentation of notation formulation we introduce 4 indices: 1) *time*, 2) *nodes* 3) *edges* and 4) *technology*. In order to improve the legibility, we predefine the validity of most indices here.

1) *Time Index* The model is defined over three time horizons: hour, day and year. Most constraints are defined over all time steps. In order to limit redundancy and improve the readability of the model, the range where time index are defined are set here and are valid for every equation where any time index is used, if not stated otherwise:

$$\begin{aligned}&\forall y \in Y \text{ with} : Y = [0, 1, \ldots, y_m]\\&\forall d \in D \text{ with} : D = [0, 1, \ldots, d_n]\\&\forall t \in T \text{ with} : T = [0, 1, \ldots, t_o]\end{aligned}$$

Each index is defined over all considered time steps from 0 until y_m, d_n and t_o, respectively.

2) *Node Index* The model includes constraints valid for different nodes and edges. We define in the following all sets used in the model. Every node and edge is assigned with specific characteristics.

We have three different kind of nodes in the model, each defined with a different set. In V_f we define all p supply nodes, in V_t all transport nodes are defined and in V_v all valve nodes.

$$\begin{aligned}V_f &= \left[v_{f,0}, v_{f,1}, \ldots, v_{f,p}\right]\\V_t &= \left[v_{t,0}, v_{t,1}, \ldots, v_{t,q}\right]\\V_v &= \left[v_{v,0}, v_{v,1}, \ldots, v_{v,r}\right]\end{aligned}$$

In addition to the node type, we set the definition of each node based on their pressure level.

$$\begin{aligned}V_{\text{hp5}} &= \left[v_{hp5,0}, v_{hp5,1}, \ldots, v_{hp5,p}\right]\\V_{\text{lp}} &= \left[v_{lp,0}, v_{lp,1}, \ldots, v_{lp,r}\right]\end{aligned}$$

All supply nodes are already defined with the same pressure boundaries, but for all demand nodes the upper and lower pressure level have to be set. Middle pressure nodes are included in V_{hp5} and low pressure nodes in V_{lp}.

3) *Edge Index* In a similar manner as for the nodes, all edges are defined over different sets.

$$\begin{aligned}E_t &= \left[e_{t,0}, e_{t,1}, \ldots, e_{t,m}\right]\\E_v &= \left[e_{v,0}, e_{v,1}, \ldots, e_{v,n}\right]\\E &= \left[E_t, E_v\right]\end{aligned}$$

Edges which represents transport pipelines are defined in E_t and edges directly connected to a valve are set in E_v. All edges are included in E, as the connection between the two nodes v and w.

The basic concept of the indices are illustrated in Fig. 1. The example includes 2 supply nodes, with two $hp5$ sub-grids. The high pressure grids are connected with 3 different valve nodes to the low pressure grids.

4) *Technologies* In the optimization model different technologies are used as index.
   - Co-generation units: chp
   - Gas boilers: b
   - Heat pumps: hp
   - Pipelines: pl

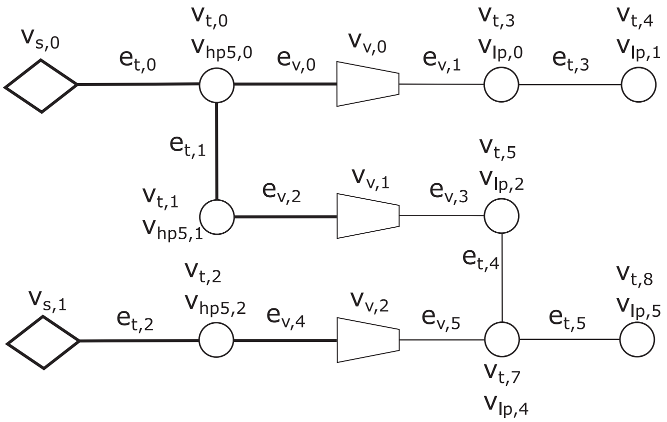


Fig. 1. Sketch of network to visualize the index concept.

2.2. *Definition of variables and parameters*

The model is defined in the following, with the objective function represented in equation (1) which is subjected to a set of constraints described in section 2.4. A nomenclature for the variables and parameters for the model is given in Appendix A. Variables are given in big letters, with binaries always as B. Parameters are used either in Greek or small letters, apart from the coefficient of performance, where COP is an universal used abbreviation.

2.3. *Objective function and compact formulation*

The optimization problem is defined as a Mixed Integer Linear Program (MILP) with the maximization of the total welfare of the heating and gas transport system, which includes all costs and incomes of the system as a whole.

The objective function is defined as following:

$$\max_{\Omega}\left(\sum_{y} E_{\mathrm{chp},y}\cdot p_y^{elec}-\sum_{u}\left(C_u^{inv}+C_u^{om}\right)\right) \tag{1}$$

$$u\in[\mathrm{pl},\ \mathrm{hp},\ \mathrm{b},\ \mathrm{chp}]$$

with the set of decision variables without their index (see nomenclature):

$$\Omega=\left(\begin{matrix}Q^{\mathrm{pl\ rebuild}}, B^{\mathrm{pl}}, C^{\mathrm{inv}}, C^{\mathrm{om}}, E, H^{\mathrm{cap}},\\ G, H^{\mathrm{rebuild}}, P, Q^{*}, Q^{\mathrm{demand}}, Q^{\mathrm{supply}}\end{matrix}\right)$$

subject to:
Equation: 2 - 6: Gas-grid configuration.
Equation: 7 - 9 and 13 - 26: Gas physics in the pipeline.
Equation: 27 - 38: Heat generation systems.
Equation (39): Heat demand-supply balance.

The costs of the system are defined as costs leaving the system, such as installation of new heating units and network parts, or for operational and maintaining costs for all units u and all energy forms r. The costs for the pipelines and the heating units are defined for the investment in 5 and 37, for the operation in 6 and 38, respectively.

2.4. *Constraints*

The topology of the network is defined with the binary decision variables $B^{pl}_{v,w,y}$, which is equal 1 when the pipeline connection between node v and w exists and otherwise 0.

$$B^{pl}_{v,w,0}+B^{pl}_{w,v,0}=1 \quad \forall v,w\in E \tag{2}$$

$$B^{pl}_{v,w,y}+B^{pl}_{w,v,y}\leq 1 \quad \forall v,w\in E \tag{3}$$

For each pipeline connection between node v and w the year of amortisation of this specific pipe is introduced here with $b^{at}_{v,w,y}$. When the year of amortisation is reached or the connection in the previous step was already computationally abandoned, the connection can only be kept, if the pipe is rebuilt, thus setting $B^{\mathrm{pl\ rebuild}}_{v,w,y}=1$ in the considered year y.

$$B^{pl}_{v,w,y-1}\cdot\left(1-b^{at}_{v,w,y}\right)+B^{\mathrm{pl\ rebuild}}_{v,w,y}\geq B^{pl}_{v,w,y}\,\forall v,w\in E_t \tag{4}$$

The installation costs for pipeline connections (equation (5)) are based on the $B^{\mathrm{pl\ rebuild}}_{v,w,y}$. If it is set to 1 for a specific time step the costs are calculated with the capital costs for all upcoming years in the considered time horizon. The operational costs (equation (6)) are calculated by introducing pipeline length-dependent costs parameters for every year (see section 5.2).

$$C^{inv}_{pl}\geq\sum_{y}\left(\sum_{v,w\in E}B^{\mathrm{pl\ rebuild}}_{v,w,y}\cdot c^{\mathrm{inv}}_{pl}\cdot\mathrm{anf}_{pl}\cdot\sum_{a\in[y,y_m]}d^{year}_{a}\right)\forall v,w\in E_t \tag{5}$$

$$C^{om}_{pl}\geq\sum_{e\in E_t,y}B^{pl}_{v,w,y}\cdot l_{v,w}\cdot c^{\mathrm{op}}_{pl}\cdot d^{\mathrm{year}}_{y}\,\forall v,w\in E_t \tag{6}$$

Pressure Level The network is subject to the natural gas flow and its pressure in the pipelines. Each pipeline has a designed pressure level, which determine the maximal and minimal pressure for its usage. The pressure must be determined at the node level, since the pressure is not constant over a pipeline length. Three different pressure types are considered here with: i) feeder (equation (7)), ii) high pressure (equation (8)) and iii) low pressure (equation (9)).

$$p^{\min}_{\mathrm{f}}\leq P_{v,t,d,y}\leq p^{\max}_{\mathrm{f}}\,\forall v\in V_{\mathrm{f}} \tag{7}$$

$$p^{\min}_{\mathrm{hp5}}\leq P_{v,t,d,y}\leq p^{\max}_{\mathrm{hp5}}\,\forall v\in V_{\mathrm{hp5}} \tag{8}$$

$$p^{\min}_{\mathrm{lp}}\leq P_{v,t,d,y}\leq p^{\max}_{\mathrm{lp}}\,\forall v\in V_{\mathrm{lp}} \tag{9}$$

Standard Pipeline Equation The standard pipeline equation is a non-linear function to estimate the pressure drop between two points in a pipeline with the square of the gas flow, general formulated as:

$$p_1-p_2=C\cdot\frac{f\cdot l\cdot sg\cdot q^2_{1,2}}{d^5} \tag{10}$$

with the Moody's friction factor f, the length l of the pipe, the specific gravity of the gas relative to water sg, the diameter d and a constant value C.

To avoid the non-linearity we introduce a new set of auxiliary variables Q^{*} which discretizes the non-linear function with the discretization index s. The gas flow Q is now defined as the sum of Q^{*} over s. Instead of the gas flow Q, we use the new definition of equation (11) and, for Q^2, we introduce equation (12) in the following model.

$$Q_{v,w,t,d,y} = \sum_s Q^*_{v,w,t,d,y,s} \, \forall (v,w) \in E_t \tag{11}$$

$$Q^2_{v,w,t,d,y} = \sum_s a^*_s \cdot Q^*_{v,w,t,d,y,s} \, \forall (v,w) \in E_t \tag{12}$$

The square of Q is thus calculated with Q^* and a pre-defined function a^* for every s, approximating the original function in the respective interval. We combine all pipeline relevant parameters together within the new parameter $\kappa_{v,w}$, for every pipeline between the two nodes v and w.

$$P_{v,t,d,y} - P_{w,t,d,y} = \begin{cases} \kappa_{v,w} \cdot \sum_s \left(a^*_s \cdot Q^*_{v,w,t,d,y,s} \right), & \text{if } B^{pl}_{v,w,y} = 1 \\ \mathbb{R}, & \text{otherwise} \end{cases} \tag{13}$$

$$\kappa_{v,w} = \frac{8 \cdot l_{v,w} \cdot f_{v,w} \cdot \rho_{v,w}}{\pi^2 \cdot d^5_{v,w}} \forall (v,w) \in E \tag{14}$$

To ensure the auxiliary variables $Q^*_{v,w,t,d,y,s}$ are assigned in the correct way regarding their index s we add equations (15)–(17) in our model. For every s in the function a^*_s we introduce the maximal value possible $q^{\max}_s$. If a pipeline is transporting a gas flow greater than $Q^*_{v,w,t,d,y,s} \cdot q^{\max}_s$, the equations will ensure that $Q^*_{v,w,t,d,y,s+1}$ is greater than 0 until all gas is distributed in the auxiliary variables over s.

$$Q^*_{v,w,t,d,y,s} \geq 0 \quad \forall v,w \in E_t \tag{15}$$

$$q^{\max}_{s+1} \geq Q^*_{v,w,t,d,y,s} \quad \forall v,w \in E_t \tag{16}$$

$$\frac{Q^*_{v,w,t,d,y,s-1}}{q^{\max}_s} - \frac{Q^*_{v,w,t,d,y,s}}{q^{\max}_{s+1}} \geq 0 \quad \forall v,w \in E_t \tag{17}$$

Gas Flow Balance It has to be ensured that the (material) balance of natural gas at each node (equation (19)) and the whole system (equation (18)) is observed. Equation (18) is redundant, since it is already covered in equation (19), but it is given explicitly, in order to facilitate comprehension.

$$\sum_{v \in V_f} Q^{\text{supply}}_{v,t,d,y} - \sum_{v \in V_t} Q^{\text{demand}}_{v,t,d,y} = 0 \, \forall v \in V \tag{18}$$

The gas flow balance at each node is determined by the gas flow coming from each neighbouring node x of considered node v, stored in E^n_v, and the flow corresponding to the node demand (leaving the system). The latter thus represents the supply entering the (heating) system at this node.

$$\sum_{x \in E^n_v} \left(\sum_s Q^*_{v,x,t,d,y,s} - \sum_s Q^*_{x,v,t,d,y,s} \right) - Q^{\text{supply}}_{v,t,d,y} + Q^{\text{demand}}_{v,t,d,y} = 0 \tag{19}$$

$\forall v \in V$

The demand for gas is determined by summing the two demand variables for the boilers and co-generation units.

$$Q^{\text{demand}}_{v,t,d,y} = G_{b,v,t,d,y} + G_{chp,v,t,d,y} \quad \forall v \in V_t \tag{20}$$

Valves The pressure level in each node is limited by equations (7)–(9) and determined by equation (13). Valves regulate the pressure and are able to lower it by $\Delta p^{\max}$. A valve installed at node v is connected to its in and out-going nodes v_0 and v_1. Since the direction of the valve is not predefined, the pressure drop always appears between the node v and v_0.

$$P_{v,t,d,y} - P_{v_0,t,d,y} \geq \Delta p^{\max} \quad \forall v \in V_v \tag{21}$$

$$P_{v_0,t,d,y} - P_{v,t,d,y} \geq \Delta p^{\max} \quad \forall v \in V_v \tag{22}$$

In a similar fashion to the gas flow balance at supply and demand nodes, we apply a gas flow balance on the valve nodes for both directions.

$$\sum_s Q^*_{v,v_0,t,d,y,s} - \sum_s Q^*_{v_1,v,t,d,y,s} = 0 \, \forall v \in V_v, \, \forall (v_0, v_1) \in E_v \tag{23}$$

$$\sum_s Q^*_{v_0,v,t,d,y,s} - \sum_s Q^*_{v,v_1,t,d,y,s} = 0 \, \forall v \in V_v, \, \forall (v_0, v_1) \in E_v \tag{24}$$

The valves can work in both directions but are excluded from the decision optimization process as such. Existing valves will stay installed over the whole time horizon, while their operation and maintenance costs are neglected.

$$B_{v,v_0,y} + B_{v_0,v,y} = 1 \, \forall v \in V_v, \, \forall (v_0, v_1) \in E_v \tag{25}$$

$$B_{v,v_1,y} + B_{v_1,v,y} = 1 \, \forall v \in V_v, \, \forall (v_0, v_1) \in E_v \tag{26}$$

We assume three technologies for existing buildings: i) conventional gas boilers, ii) natural gas-supplied co-generation units and iii) power-driven heat pumps. Both models for the two technologies fed by natural gas are very similar and are therefore put together with the index for unit u.

Natural gas-supplied technologies We define the capacity for each heating unit (boiler or CHP) with the capacity installed in year y in all buildings attached to node v. In $r^{\text{unit}}_{u,v,y}$ we define pre-model-wise the distribution of existing heat technology u in node v for year y. Based on the amortisation year, we are able to determine the year the considered heating unit has to be replaced. The cumulative capacity of existing heating units is assumed to be designed to handle the peaks in our initial demand calculations, represented by $max(h^{\text{heat}}_{v,t,d,y=0})$. Both parameters can be combined in equation (27) to $h^{\text{at}}_{u,v,y}$, which can be interpreted as the disappearing capacity of each initial installed unit u in every year y and node v.

$$h^{\text{at}}_{u,v,y} = max\left(h^{\text{heat}}_{v,t,d,y=0}\right) \cdot r^{\text{unit}}_{u,v,y-1} \quad \forall u \in [b, chp], \, \forall v \in V_t \tag{27}$$

Equations (28) and (29) represent the balance of the heat capacity in the previous annual time step, the additional installed capacity, and the disappearing of predefined capacity in considered year y.

Heating unit capacity assigned by the optimization process is also subject to its amortiation time. Heating units with an amortisation time need to be replaced after n years. In order to consider this in the balance, we separate the balance into two equations, since $H^{\text{rebuild}}_{u,v,y-n}$ is not defined for $y < n$. The following equations are all defined with:

$\forall u \in [b, chp]$ and $\forall v \in V_t$.

$$H^{\text{cap}}_{u,v,y} = H^{\text{cap}}_{u,v,y} + H^{\text{rebuild}}_{u,v,y} - h^{\text{at}}_{u,v,y} \quad \forall y \in [0, \ldots, n] \tag{28}$$

$$H^{\mathrm{cap}}_{u,v,y} = H^{\mathrm{cap}}_{u,v,y-1} + H^{\mathrm{rebuild}}_{u,v,y} - H^{\mathrm{rebuild}}_{u,v,y-n} - h^{\mathrm{at}}_{u,v,y} \quad \forall y \in [n,\dots,y_m] \tag{29}$$

The capacity is used as the upper boundary in equation (30) for heat production in every time step, with the gas demand $G_{u,v,t,d,y}$ and fixed gas and technology parameters.

$$H^{\mathrm{cap}}_{u,v,y} \geq \eta^{\mathrm{heat}}_{u} \cdot h^{\mathrm{gas}} \cdot G_{u,v,t,d,y} \tag{30}$$

The difference between the model for the co-generation and the conventional gas combustion unit lies in the consideration in the objective function as a passive income for the system due to the production of electricity. For the case that the public acceptance vary for different technologies, no new capacity for heat unit u is allowed after year m.

$$E^{\mathrm{chp}}_{y} = \sum_{\forall v \in V_t} \frac{G_{chp,v,t,d,y} \cdot \eta^{\mathrm{heat}}_{chp} \cdot h^{gas}}{\Theta} \tag{31}$$

The amount of electricity produced is directly related to the heat generated and the technology relevant parameter Θ, representing the heat to electricity ratio. The decision variable $G_{chp,v,t,d,y}$ gives the amount of gas in node v in order to generate the required heat with the CHP unit.

$$H^{\mathrm{cap}}_{u,v,y} = 0 \quad \forall y < m, \forall v \in V_t \tag{32}$$

Heat Pump Model The model for heat pump systems is based on the heating capacity and the electricity demand, hence generating the requested heat on demand side. We determine the capacity in a similar fashion to equation (29), i.e. as a balance between the capacity in the previous time step, the newly installed capacity and the disappearing capacity due to amortisation of heat pumps installed in previous time steps $y-n$. The production of heat via heat pumps is based on the capacity as the upper boundary and the COP of the unit, which is considered to be dependent on its node position. The following equations are all defined: $\forall v \in V_t$.

$$H^{\mathrm{cap}}_{hp,v,y} = H^{\mathrm{cap}}_{hp,v,y-1} + H^{\mathrm{rebuild}}_{hp,v,y} \quad \forall y \in [0,\dots,n] \tag{33}$$

$$H^{\mathrm{cap}}_{hp,v,y} = H^{\mathrm{cap}}_{hp,v,y-1} + H^{\mathrm{rebuild}}_{hp,v,y} - H^{\mathrm{rebuild}}_{hp,v,y-n} \quad \forall y \in [n,\dots,y_m] \tag{34}$$

$$H^{\mathrm{cap}}_{hp,v,y} \geq \mathrm{COP}_v \cdot E_{hp,v,t,d,y} \tag{35}$$

In order to limit the installation of heat pumps per year, we regulate the total new heat pump capacity per year with hp^{reg}_{y}.

$$\sum_{v} H^{rebuild}_{hp,v,y} \leq hp^{reg}_{y} \tag{36}$$

Unit Costs Constraints The constraints to calculate the investment costs for new heating units (equation (37)) are similar for all three technologies and are calculated with the capital costs for the years of amortisation after a new unit is installed in year y with the new capacity $H^{\mathrm{rebuild}}_{u,v,y}$. The operation costs (Eq: 38) are calculated with a constant price per unit parameter and the amount of years represented with year y. Since the cost functions are used for all three heating units, $\forall u \in [b, chp, hp]$ is valid.

$$C^{inv}_{u} \geq \sum_{v,y} \left(H^{\mathrm{rebuild}}_{u,v,y} \cdot c^{\mathrm{inv}}_{u} \cdot \mathrm{anf}_{u} \cdot \sum_{a \in [y,y_m]} d^{\mathrm{year}}_{a} \right) \quad \forall v \in V_t \tag{37}$$

$$C^{om}_{u} \geq \sum_{v,y} \left(H^{\mathrm{cap}}_{u,v,y} \cdot c^{om}_{u} \cdot d^{\mathrm{year}}_{y} \right) \quad \forall v \in V_t \tag{38}$$

Heat Demand-Supply Balance The heat production is defined by the related primary energy and a conversion parameter. In each time step, the pre-determined heat demand $h^{\mathrm{heat}}_{v,t,d,y}$ has to be covered. The demand gets then covered in two ways: i) outside and, ii) inside the optimization. Outside the optimization, we assume that all buildings that do not have natural-gas based technologies do cover their heat demand until these units are amortized. The percentage in every node v of the heat demand covered outside of the optimization is summed up in the sum of $r^{\mathrm{unit}}_{u,v,y}$ with U_{div} as different technologies (e.g. wood and oil combustion). In turn, the heat demand that is not covered outside of the optimization needs to be covered by the three previously mentioned heating technologies.

$$\begin{aligned} &\sum_{u \in [b,chp]} G_{u,v,t,d,y} \cdot \eta^{\mathrm{heat}}_{u} + E_{hp,v,t,d,y} \cdot \mathrm{COP}_v = \\ &h^{\mathrm{heat}}_{v,t,d,y} \cdot \left(1 - \sum_{u \in U_{div}} r^{\mathrm{unit}}_{u,v,y} \right) \quad \forall v \in V_t \end{aligned} \tag{39}$$

3. Test-case Geneva

The Canton of Geneva is at the same time one of the smallest cantons within the Swiss Confederation albeit one of the most dense, with almost 500,000 inhabitants distributed over less than 300 km^2. It relies on an extended and densely meshed natural gas distribution network, supplied both from its Western and Eastern boundaries (see Fig. 2). Since many years, Canton of Geneva is pursuing a broad policy fostering increased energy efficiency in the building sector, with a palette of subsidies aimed at supporting buildings refurbishment. Like other Swiss cantons, Canton of Geneva intends to decrease the share of fossil fuels for space heating applications; however, natural gas is considered to be a transition energy vector, that allows significant decrease of GHG emissions in the buildings sector upon replacement strategy from oil-based boilers (still covering a substantial part of the space heat demand). Concomitantly, power-driven heat pumps and district heating networks are being favoured at policy level. Mini- and micro-cogeneration are presently almost absent in the Canton of Geneva, although they are considered as viable solutions in Energy cantonal strategies due to high exergetic efficiency and possible role in covering power supply after the decision to gradually close Swiss operating nuclear power plants. Direct natural gas boilers are expected to get forbidden at Federal level, putting at risk the further evolution of the natural gas network in the Canton of Geneva and other Swiss cantons, along with its economic viability (due to usually very long amortisation times). Hence, the extension of the natural gas distribution network is expected to either stabilize or decrease in the future years, in parallel with decreasing energy demand in the residential sector, possibly leading to increased OPEX costs and connection fees for final users.

4. Data harvesting, preparation and validation

The optimization model thoroughly described below has been applied to the heating system of the Swiss Canton of Geneva. In collaboration with the local multi-energy utility, Services Industriels de Genève (SIG), and open data from the cantonal territory information system (SITG) [27] the whole heating system has been

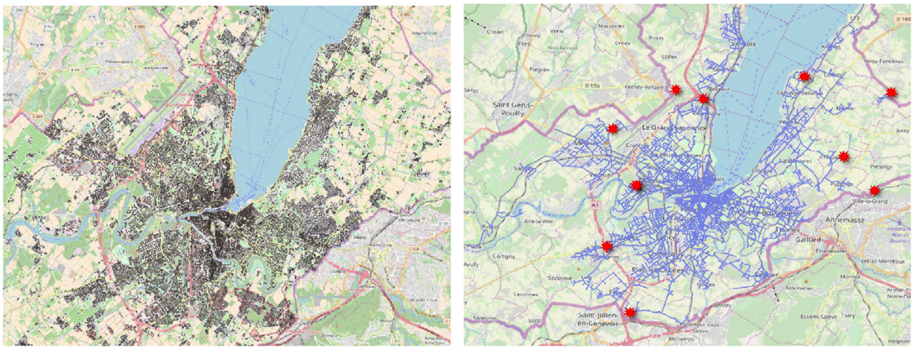


Fig. 2. Map of the canton of Geneva with all buildings (left) and gas pipeline network with its injection points (right).

modelled on the scale of the gas distribution pipelines. The system modelling is based on two levels. First, on the gas pipeline network level and second, on the buildings level, thus providing a transparent link between energy supply and demand.

(1) *Pipeline Network* The gas pipeline network creation is fully based on non-public data provided by SIG, which owns, operates and monitors the former. The natural gas distribution grid has a total length of 675 km over the whole canton, with 2475 valves. In this work, the pipeline attributes taken into consideration are the following: diameter, installation or maintaining date, pressure level and the length over which the parameters are constant. Fig. 3 illustrate the distribution of pipelines regarding their construction year and diameter. The utility strategy aimed at using smaller pipeline diameters in order to decrease costs and increase the transport velocity can be observed in the diagram. In order to decrease computation power for the optimization, we reduced the complexity of the network by combining edges and complex structures. The raw data with around 45,000 nodes and 48,000 edges was reduced towards 6000 nodes and 6800 edges, while keeping important information.

(2) *Building* For each building in the Canton of Geneva, we gathered detailed information given by SITG This information include on the buildings side: its classified type, the construction or refurbishment year and characteristic building size parameters. With the information of the building type, the construction year and the basic geometric information of each building, missing heat surface (SRE) values have been estimated using a linear rule. The required information on the local heating system sides include: the installed technology the used energy carrier, the installed capacity of the heating system and the year of its implementation (see Fig. 4). In this project only areas which are already connected or are close to the gas pipeline grid and are therefore potential gas customers, are part of the considered system.

(3) *Full System* The two levels of data preparation are eventually combined in a third step, in order to keep the optimization on the pipeline network level. The information coming from the building level are connected to the pipeline network, in such a way as to obtain a graph with the building information at each node and pipeline information at each edge. Via a shortest distance algorithm, each building in the network is connected to its closest node of the gas network.

Heat demand profiles The heating and natural gas system created in the steps described above is static and is not subject to any changes. The operation of an heating system is however a dynamic process which is strongly influenced by customer behaviour and other external impacts. Based on historical real measured data from a selected neighbourhood of Geneva, an algorithm was developed in order to create a heat load for each hour in one year ([28]). The created load profiles are successively used to identify representative days, which are clustered towards representative time steps as well. The results of both procedures, the heat profile creation and the clustering are illustrated in Fig. 5.

In our study, we additionally consider a dynamic change in future heat demand due to policies fostering the refurbishment of energy-inefficient buildings. In this context, the Canton of Geneva aims a refurbishment rate of around 2% per year, in order to lower heat demand and, by that, contribute to GHG emissions reduction. We use the information of the age and the type of each building to identify the likelihood for refurbishment in each municipality of the Canton of Geneva. Hence, our modelling approach can effectively take into account buildings retrofitting policies and thus stays close to territorial energy planning dynamics, useful for both local authorities and utilities involved in energy efficiency endeavours.

5. Optimization solution and parameters

5.1. Optimization solving

The MILP described in section 2 was solved for the test case of Geneva with Gurobi 7.5.2 in Python 3.6 [29] on different local office computers. Gurobi is a commercial program, however, academic licenses are free of charge, which were used to solve the optimization model. The solver identified in total 858,480 general constraints with 2,164,339 continuous, 171,696 integer, and 171,686

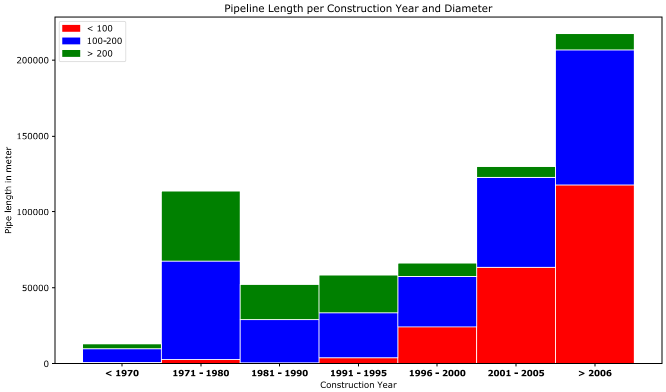


Fig. 3. Pipeline diameters and installation years of the gas grid in Geneva.

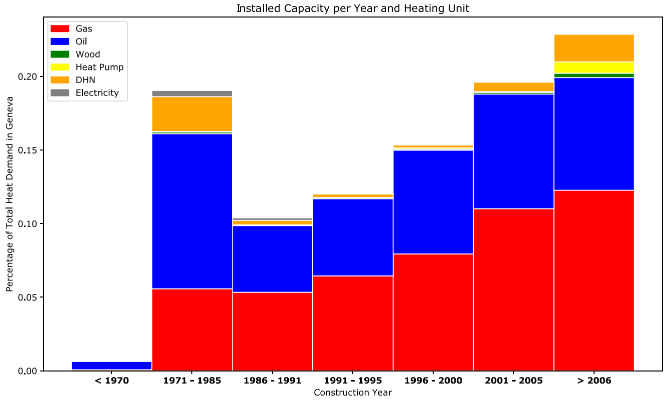


Fig. 4. Distribution of local combustion heating system based on primal energy carrier and installation age.

binary variables for the given test case. An optimal solution was found by using the Simplex Algorithm after a calculation time of around 3 h per scenario. The Simplex Algorithm solves linear programming problems iterative over the extreme points of the model and checks for an optimal and feasible solution for the given constraints.

5.2. Parameters

The optimization model is applied to the test case of Geneva. The parameters used to represent this test case are given in the following.

In addition to the network configuration data from section 4, we set costs parameters for the pipeline system in Table 1. The pipeline parameters are approximations based on discussions with experts of the Geneva gas-network.

The parameters used to model the heating system are given in Table 2. The technological parameters for heat pumps are adjusted to fix the better availability and costs regarding the GeniLac project. If not mentioned differently, all parameters used in this project for the heating system were taken from Ref. [30].

Parameters which are subject to strong uncertainty but are expected to have a strong impact on the results are listed in Table 3. For each parameter, we chose three different values a,b and c used to create scenarios for the optimization model.

The regulation for the installation of gas combustion boilers are a matter of controversies. We assume that this disable all new constructed building from installing a gas based heating unit. Already existing buildings with a gas infrastructure are still allowed to renew the gas boiler during the first 10 years of the calculation until 2030.

Table 1
Pipeline costs parameters.

Parameter	Value	Unit
Investments Costs	8000−12000	CHF/m
Operation Costs	70	CHF/m • year
Amortisation time	40	years

Table 2
Heat technology parameters.

Parameter	Value	Unit
Boiler η_{therm}	0.9	–
CHP η_{therm}	0.65	–
HER	2.5	–
H_{ugas}	10	kWh/m3
Boiler Capital cost	600	CHF/kW
Boiler OM costs	0.025	$\%_{inv}$/year
CHP Capital Costs	2000	CHF/kW
CHP OM Costs	0.05	%
COP	3 (3.5 for GeniLac)	–
HP Capital Costs	2000 (1500)	CHF/kW
HP OM Costs	0.015	%
Amortisation time	20	

Table 3
Pricing parameters.

	A	b	c	Unit
Gas	0.07	0.11	0.15	CHF/m3
Elec (buying)	0.15	0.2	0.25	CHF/kWh
Elec (selling)	0.03	0.05	0.07	CHF/kWh
Refubishment	−0.04	0	0.04	–

6. Results

The optimization algorithm presented above has been applied to the whole territory of the Swiss Canton of Geneva with the parameters mentioned in section 5.2. This choice is label as “benchmark scenario” and the corresponding results are shown in the first section below. The second section, in turn, presents an overview regarding the impact of the variation of the model parameters.

6.1. Benchmark scenario

Heat Capacity The installed capacity for heat generation in the

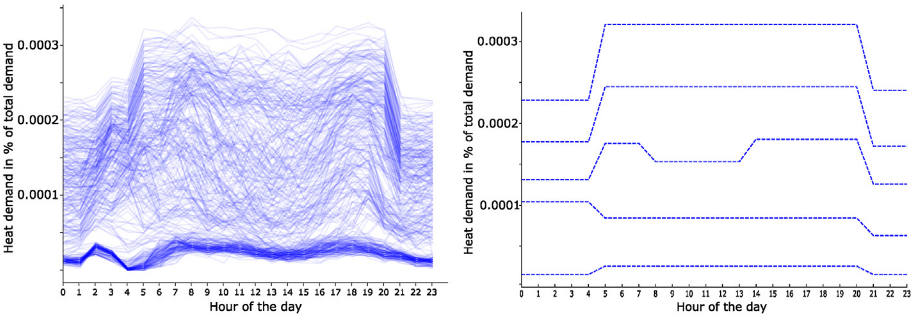


Fig. 5. Annual heat demand profile, left: results of profile creation, right: representative days with clustered hours.

Canton of Geneva will fundamentally evolve over the next 40 years, since political regulations are intended to reduce the usage of fossil fuel based combustion units. The benchmark scenario parameters were used within the algorithm with the restriction of no new oil or wood based combustion units and a penetration rate of new heat pumps amounting to 20 MW_{elec} per year.

In Fig. 6, the evolution of the heat capacity is shown over the next 40 years. We assume an approximately even distribution between oil and natural gas based boilers in the initial time step. As mentioned in section 4 there is a large part of older oil furnaces, but also gas based boilers which need to be replaced. The blue bar represents the capacity of heating units, which are not directly considered in the optimization model. The capacity of these units disappear nearly linearly, with the remaining part left in 2050 representing the existing district heating network located close to the natural gas network. The disappearing capacity is mostly covered by new gas boilers in the first two five-year periods and, to a lower extent, by way of CHP units and heat pumps. In 2030, no new gas boilers installation are allowed and, in the following years, the installed capacity of gas boilers decreases gradually, with a steep decrease in 2045. The capacity still available in 2045 is given by the new gas boilers installed in 2020 and 2025, while the capacity of 2050 represents only the new capacity installed in 2025. When the amortisation time of the gas boilers installed in 2020 ends (i.e. in 2040), we see a strong rapid increase of new CHP units, covering the new capacity. Heat pumps cover a relatively small amount of the initial free capacities but, with the disappearing of gas boilers, new heat pumps increase significantly after 2040.

Pipeline Evolution Any heating system is subject to different restrictions. An important one when considering gas based units, is the existence of transport and distribution infrastructures. The results for the heat capacity are only possible if the gas transportation is still functioning at every time step. Similar to the capacity model, each pipeline segment is characterized by its amortisation time and related operational costs. The evolution of the total length of the network is shown in Fig. 7.

Pipeline segments that are identified as unnecessary are abandoned in the first annual time step. In the following years, the total length decreases only slightly, linked to the disappearing gas based boilers and pipeline amortisation in this time step. The total network length is reduced over 40 years by around 100 km. However, as can seen in Fig. 8, there is no island effect or full areas where the natural gas distribution grids gets erased. In the close up of the downtown area it can be seen that the grid gets indeed less dense, losing mainly peripheral branch. Small neighbourhoods, which are represented by nodes are fully supplied by heat pumps and are not connected anymore to the natural gas grid. This enables gas transport capacities to close by nodes to which CHP units are connected.

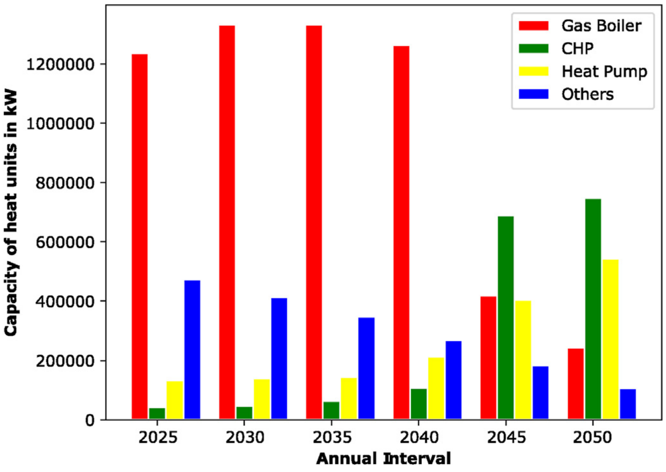


Fig. 6. Evolution of heat unit capacities over 50 years.

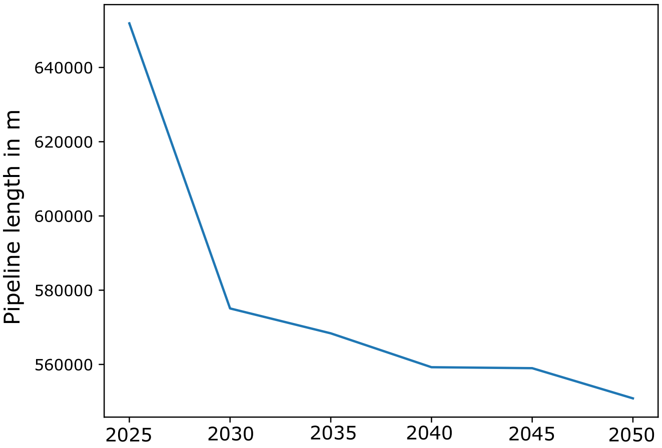
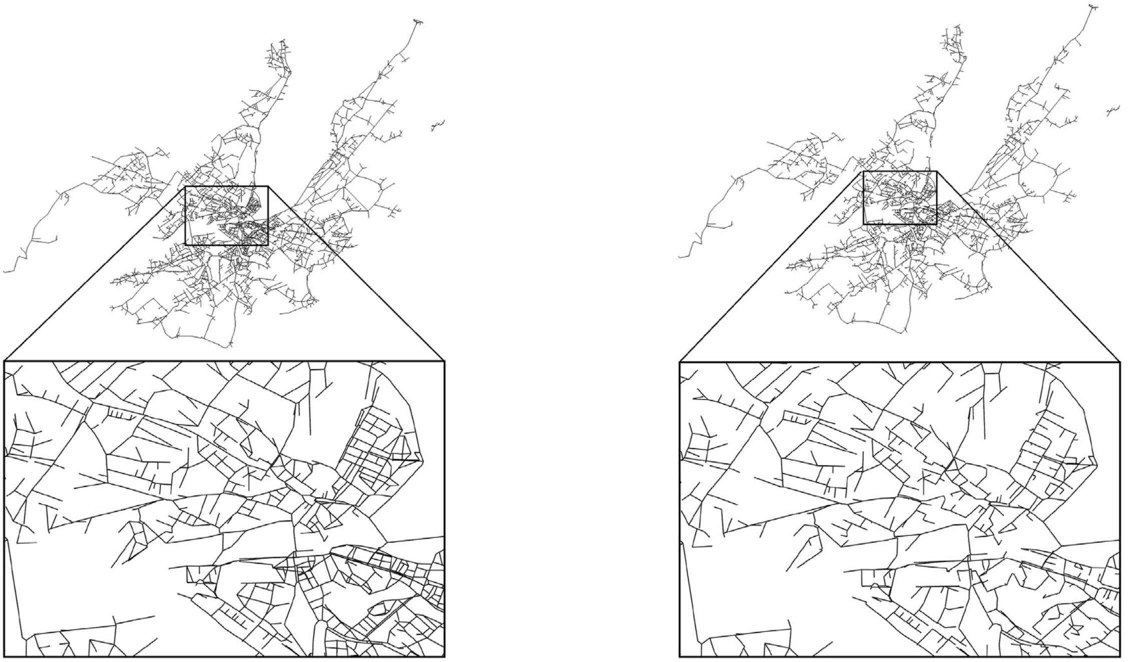


Fig. 7. Length of Gas network.

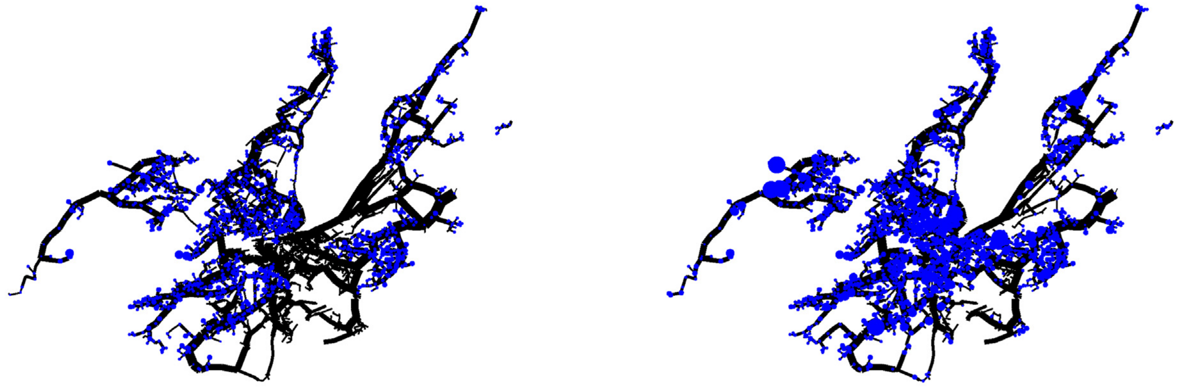
Heating Unit Distribution Combining the results of both previous subsections, we can locate the evolution of the capacity of heating units in the considered network. While new gas boilers are also installed in the first 10 years, we exclusively focus on the capacities of CHP units and heat pumps in the following. On Figs. 9 and 10, the evolution of the capacity for CHP units and heat pumps are illustrated. In addition to the geolocation of the units, the capacity is indicated with the size of the dot and for Fig. 9 the gas flow with the thickness of the network. In both figures, the distribution of the capacity for each representative unit is shown for different annual time steps. In the first sub-figure a), the installation of new units between 2020 and 2025 can be seen. While the distribution of initial installed CHP units (9 a)) are rather evenly distributed over the whole area in small capacity units, heat pumps are initially distributed in a concentrated fashion around downtown City of Geneva in larger single units. In the following annual time steps, the installations of both technologies are equally distributed over the considered system.

CO_2 Emissions The heating demand of Geneva is presently mostly covered by natural gas and oil combustion units. More recent political regulations aim at decreasing emissions of the heating sector and thus tend to be restrictive on these technologies. Based on the $CO_{2(\text{equivalent})}$ values given by the KBOB [31], the GHG emissions over the considered time horizon were estimated and are shown on Fig. 11. The GHG emissions are linked to the heat production which, in turn, depends on the heat demand. While the emissions are not directly depending on the capacity of the different heating units, it can be observed that the big gap between 2040 and 2045 is concomitant to the disappearing of gas boilers illustrated on Fig. 6. In total, the GHG emissions drop by over 50% in the following 40 years, with the disappearing of combustion boilers as the biggest driver. But it should be clarified that the KBOB calculates the emission parameters for CHP units, without the production of electricity. In a complete energy balance that would consider electricity production as well, the emissions attributed to CHP would then be slightly larger.

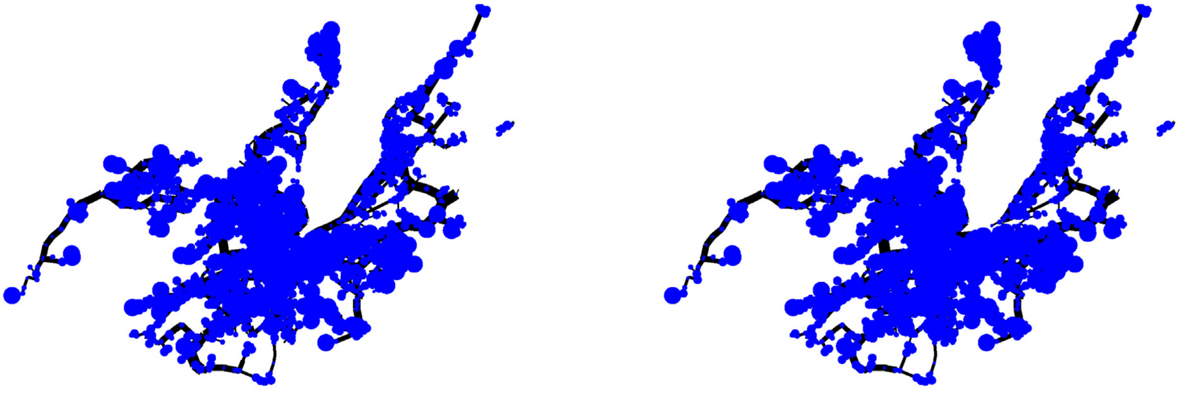

(a) Initial gas-network in 2020

(b) Gas-network in the final calculation step 2050

Fig. 8. Evolution of the gas-pipeline network of Geneva.

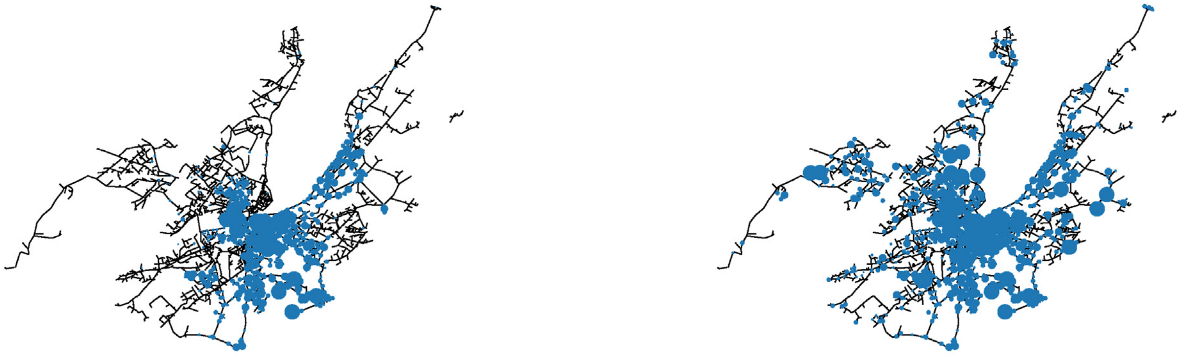

(a) 2020 - 2025

(b) 2035 - 2040

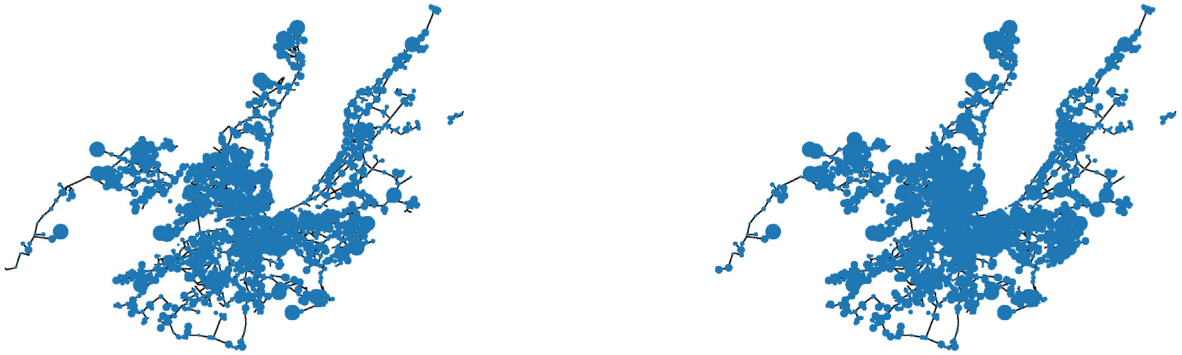

(c) 2040 - 2045

(d) 2045 - 2050

Fig. 9. Distribution of CHP capacities installed in Geneva, with the gas flow in the pipeline network on the peak day for different annual intervals.



(a) 2020 - 2025   (b) 2035 - 2040



(c) 2040 - 2045   (d) 2045 - 2050

Fig. 10. Distribution of heat pump capacities installed in Geneva, with the pipeline network for different annual intervals.

6.2. Sensitivity analysis on the benchmark scenario

The optimization algorithm uses parameters which the authors identified as benchmark values, i.e. rather close to real figures for the Swiss context. By varying the parameters, different scenarios allowed identifying the impact of the somewhat arbitrary choice, as well as the robustness of the optimization framework results. The scenarios of variations of the gas price and the electricity price are based on the work of [30] for the Canton of Geneva. In addition we identified the selling price for electricity produced by the CHP unit and the refurbishment rate of buildings in Geneva as important parameters to investigate. Each scenario represents a variation of one parameter and for each parameter three different values were chosen.

The evolution of CHP unit capacity for the four different scenarios is illustrated on Fig. 12. In both parts a) and b), a small decrease of the total capacity in the first four time steps appears with increasing prices, but the capacities in the final two time steps are not affected. For the building refurbishment scenario on Fig. 12 c), the opposite can be observed, the first four annual time steps are roughly identical, while the final two are significantly decreased upon more aggressive refrotting constraints. This is very likely due to the 15% lower heat demand, which results in a lower demand for heat capacities. The final scenario of the selling price for CHP produced electricity in Fig. 12 d) gives an indicator that CHP units can be competitive on a free marked if the selling price for the electricity is high enough. In our case we can observe that by 0.07 CHF per kWh electricity, CHP units are installed in some areas in the first two time steps, instead of conventional gas boilers and later also instead of heat pumps. By comparing all four scenarios, it is noticeable that the final distribution is rather similar in all case, pointing to the robustness of the optimization framework and choice of parameters.

The evolution of the heat pump capacity for the different

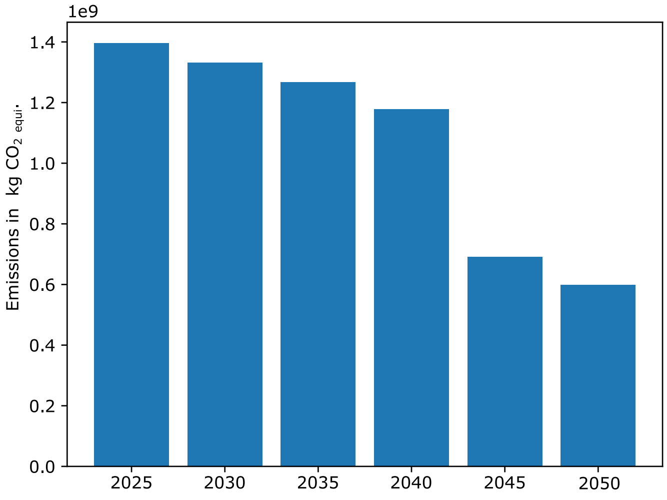
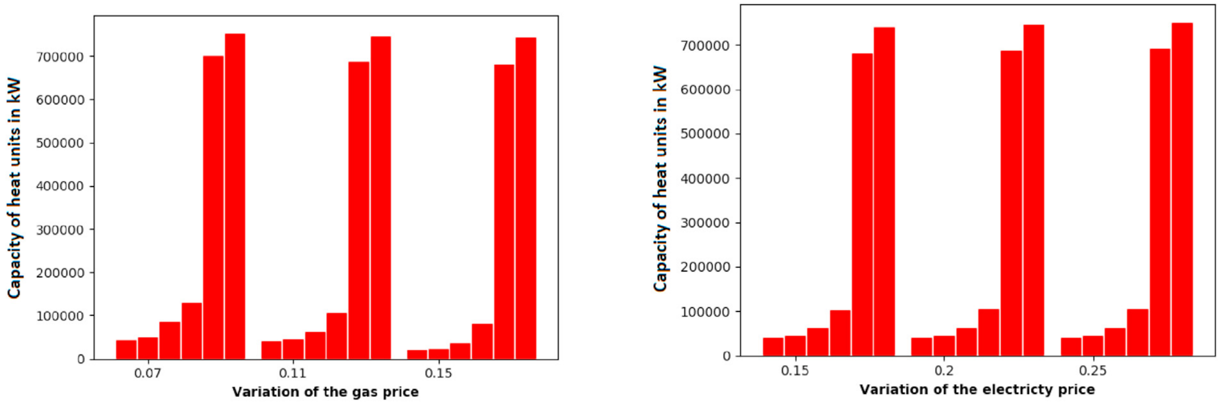
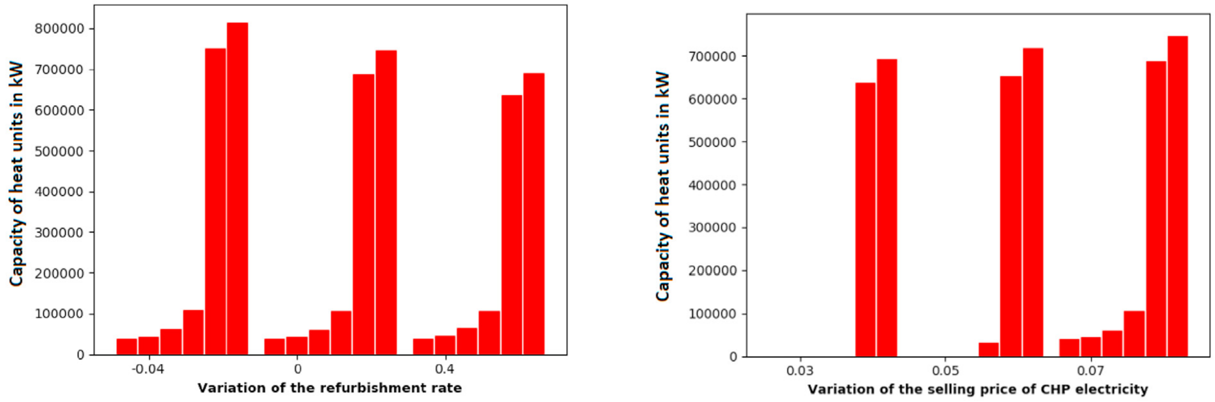


Fig. 11. CO2 emissions.



(a) Based on gas price

(b) Based on electricity price



(c) Based on refurbishment rate

(d) Based on selling price for electricity

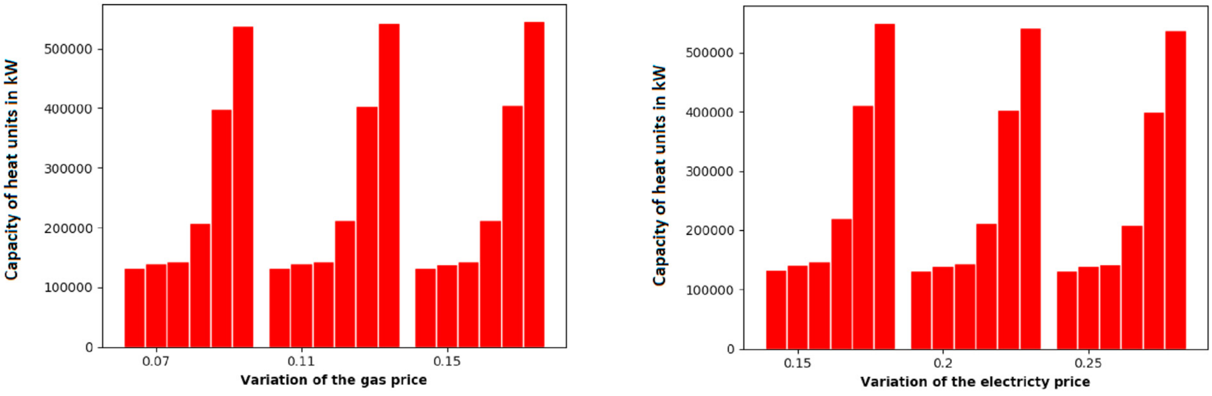
Fig. 12. Evolution of capacity for CHP units for different scenarios over the six annual time steps.

scenarios is depicted on Fig. 10. For both scenarios a) and b), no differences can be noticed. The variation of the refurbishment rate gives similar results to those obtained for the CHP capacity (see Fig. 13), with a total reduction in the final two annual time steps. Scenario c) for different selling prices of electricity shows a reduction of the capacity of heat pumps in the final time steps as well.

By comparing the evolution of both energy conversion technologies, heat pumps and CHP units, for different scenarios, it stands out that both diagrams are not mirroring each other. This suggests that both technologies are indeed not competing with each other for the heat capacity set free by the need to replace fossil-based simple boilers, at least in most cases. CHP units are indeed only installed in early time steps, if the optimization model identifies them as superior towards gas boilers.

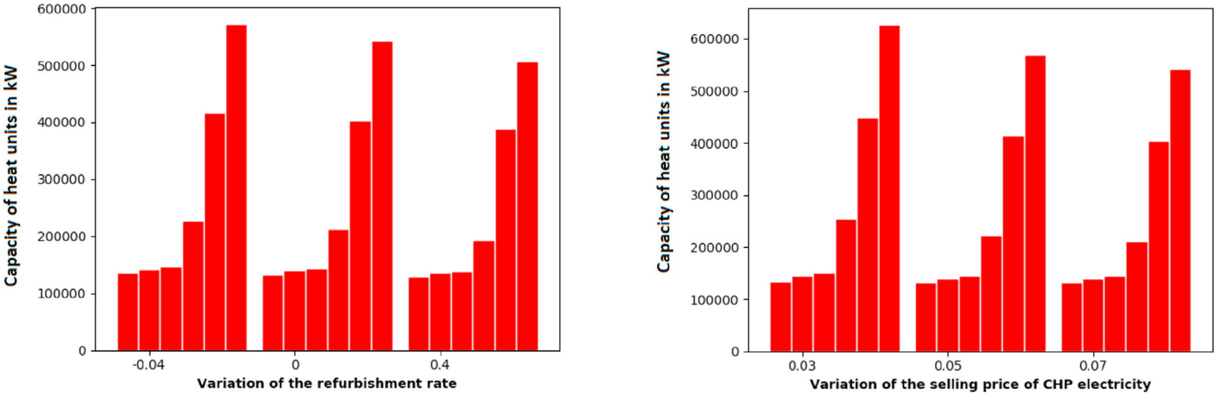
7. Discussion and perspectives

The results clearly indicate that a complete and complex natural gas distribution network over an entire region under constraints and detailed geolocalized heat demand represents a numerically tractable problem, with certain approximations. Some of these approximations could be relaxed, e.g. time granularity for future time-periods and choice of typical days, if the considered study zone is chosen to be smaller. To our knowledge, this work represents one of the first attempts to study the evolution of a natural gas distribution network under decreasing demand constraints, in order to identify grid sectors that can be abandoned – or used for other purposes, e.g. cables – to decrease overall CAPEX and OPEX. At the same time, high-efficiency technologies based on natural gas such as CHP units can be implemented on the optimized network, in order to ensure its medium- and long-term financial viability and to foster the penetration of power-driven heat pumps. Indeed, power generated by CHP unit can be valorized to cover a substantial share of the additional electricity demand arising from broad-scale heat pumps penetration on the territory. In a country like Switzerland, that must massively turn to power imports during the winter months while engaging in a nuclear phase-out, the contribution of decentralized generation units such as CHP can provide crucial support for the power grid stability and overall security of supply. This is indeed one of the main results of this paper, as can be seen in Fig. 6: the installed capacity of CHP units can cover half of the power demand generated by heat pumps at the end of the 40 years period. Moreover, as can be seen on the distribution map of CHP units on the territory of the Canton of Geneva, the latter would be distributed in a rather homogeneous fashion, thereby suggesting that they would be able to inject power in the low-voltage electricity grid, directly matching heat pumps demand. Hence, a double result can be obtained: not only the viability of natural gas network can be financially ensured, but increased CAPEX for low-voltage power distribution infrastructure reinforcement could be avoided. The optimization framework, despite its simplifications, thus



(a) Based on gas price

(b) Based on electricity price



(c) Based on refurbishment rate

(d) Based on selling price of electricity

Fig. 13. Evolution of capacity for heat pumps for different scenarios over the six annual time steps.

allows identifying territorial energy planning scenarios that build upon synergies between heat pumps and CHP units replace fossil-based direct boilers and lower GHG emissions. The crucial bridging role that the natural gas network can play in view of energy transition pathways to renewable energy sources is highlighted by the results presented in this paper, in accordance with similar conclusions drawn at national level, e.g. in Ref. [32].

Another important result from the presented optimization approach is the absence of islanding effect. This effect does not take place and, even in rather drastic building refurbishment scenarios, the overall “backbone” of the natural gas network stays intact, with the latter just showing a less dense mesh in certain zones, in particular in down-town City of Geneva. Moreover, the overall connectivity (and the associated redundancy) remains guaranteed, as can be seen on Fig. 8. In this study, natural gas has been considered on purpose as being purely fossil in nature. Hence, the GHG decrease results that are shown on Fig. 11 can be further improved with increasing share of renewable methane in the natural gas mix. Indeed, Swiss gas industry and their counterparts in most European countries, has taken ambitious commitments to increase the share of renewable gas already by 2030 or 2050. This represents an important result, since the Canton of Geneva has set precise GHG emissions goals that can be met, at least in a transition period, even by taking advantage of partly fossil-based – albeit high-efficiency – technologies. It also stresses that the gas distribution infrastructure represents a real added value, independently of the precise nature of the gaseous energy vector transported by it from supply to demand nodes.

The work presented above is based on certain simplifying hypotheses that delineate some future interesting research perspectives. First, the proposed optimization framework includes only power-driven heat pumps and cogeneration units as heat-providing technologies; the inclusion of heat exchangers supplied by low-temperature or high-temperature district heating networks is clearly needed, in order to take into account a supplementary low-emissions technology in the supply mix. This is particularly relevant for Switzerland but for other EU countries as well, where district heating network (DHN) solutions have broad political support at both local and national levels. Second, the scalability of the proposed optimization process for larger cases can be improved by applying decomposition techniques such as Bender decomposition, already used in other energy-related problems. Third, the global wealth optimization approach adopted in this paper – and in plenty of other references – must be improved, in order to take into account the different levels of stakeholders on a given territory and of the distribution of the costs among them.

Fourth, the contribution of decentralized co-generation units to generate a substantial part of the increased power demand due to heat pumps is highlighted here but the result is indeed “indirect”, in the sense that it is based on overall installed capacity, simultaneous use of such capacity in a continental-climate country such as Switzerland and homogeneous geographical distribution.

However, a more precise evaluation of such an interaction between distributed CHP and heat pumps on a real distribution network should be performed by way of dynamic simulations; such a study would allow to determine to which degree the power produced by CHP units relieves the medium-voltage feeders, particularly in cold periods and for given neighbourhood configurations. The authors are currently working on the cited framework improvements and evolutions.

8. Conclusions

An optimization framework for an entire natural gas distribution network has been developed and applied to a complete region of half-million inhabitants. A detailed mapping of both heat demand and supply on the territory of the Swiss Canton of Geneva has been realized and used as the basis to implement the optimization scheme, in addition to constraints related to the expected decrease for heat demand in the building sector and to more restrictive policies targeting fossil-based direct boilers. The optimization covers a future period of 40 years, based on five-years periods. The results highlight the evolution of the installed capacities devoted to heat production on the Canton of Geneva and, in particular, on the positive synergies between power-driven heat pumps and distribution cogeneration units. The natural gas distribution grid extension slightly decreases, all the while keeping its overall topology and redundance for the supply of the considered territory. The optimization scheme allows identifying energy planning scenarios that simultaneously take into account economic aspects, energy efficiency policy objectives and the overall endeavour aiming at decreasing GHG emissions from the energy sector.

Sample CRediT author statement

Marten Fesefeldt: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization; Massimiliano Capezzali: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition; Mokhtar Bozorg: Methodology, Resources, Writing – review & editing; Matthieu De Lapparent: Resources, Writing – review & editing, Supervision.

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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Appendix A. Supplementary data

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Nomenclature

Variables

$B^{plrebuild}_{v,w,y}$: Binary decision if pipeline is rebuild between node v and w in year y
$B^{pl}_{v,w,y}$: Binary decision if pipeline exists between node v and w in year y
C^{inv}_{u}: Total investment costs for unit u
C^{om}_{u}: Total operation and maintenance costs for unit u
$E_{hp,v,t,d,y}$: Electricity consumption for heat pumps in node v and time step t,d,y
$G_{u,v,t,d,y}$: Gas delivered to node v for heating unit u
$H^{cap}_{u,v,y}$: Heat capacity of unit u in node v and year y
$H^{rebuild}_{u,v,y}$: New installed heat capacity of unit u in node v and year y
$P_{v,t,d,y}$: Pressure level in node v in time step t,d,y
$Q^{*}_{v,w,t,d,y}$: Gas flow between node v and w in time step t,d,y
$Q^{demand}_{v,t,d,y}$: Gas flow leaving the network in demand node v in time step t,d,y
$Q^{supply}_{v,t,d,y}$: Gas flow entering the network by supply node v in time step t,d,y

Parameters

η^{heat}_{u}: Efficiency of heating unit u
Θ: Heat to electricity production ratio of CHP units
a^{*}_{s}: Help value for the linealization of the standard gas equation
$b^{at}_{pl,v,w,y}$: Binary parameter for amortisation time of pipeline between v,w
c^{inv}_{u}: Relative investment costs of unit u
c^{om}_{u}: Relative operation and maintenance costs of unit u
d^{year}_{y}: Amount of representative years for yearly time step y
$h^{at}_{u,v,y}$: Heat capacity of unit u amortises in node v and year y
h^{gas}: Heating value of natural gas
$h^{heat}_{v,t,d,y}$: Heat demand in node v for time step t,d,y
hp^{reg}_{y}: Regulation of new heat pump installation per year
$l_{v,w}$: Pipeline length between node v and w
p^{elec}_{y}: Price for electricity in year y
$r^{unit}_{u,v,y}$: Percentage of heat capacity for other heating units u not covered in the model
anf_{u}: Annuity factor for unit u
COP_{v}: coefficient of performance for heat pumps in node v