Bidirectional low temperature networks in urban districts: A novel design methodology based on mathematical optimization

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Abstract. Bidirectional low temperature networks (BLTN) are a sustainable and energy efficient concept to supply urban districts with heating and cooling. In this work, we present a linear program (LP) for designing BLTNs. Based on a superstructure, the optimal energy conversion units are selected and sized for each building connected to the network and an energy hub. The superstructure of HVAC systems in buildings comprises heat pumps, electric boilers, thermal storages, compression chillers, cooling towers and heat exchangers for direct cooling with the BLTN. Within a case study, the LP is applied to a district with 17 buildings on a research campus in Germany. The performance of the BLTN is compared to a heating and cooling supply by individual HVAC systems for each building. With a BLTN, the total annualized costs can be reduced by 42 % and the CO₂ emissions by 56 %, compared to stand-alone HVAC systems.

1. Introduction
In Europe, 50 % of the final energy consumption are caused by heating and cooling applications [1]. Nowadays, cooling loads are often covered by decentral chillers and air-conditioning units. Thus, waste heat from cooling processes often remains unexploited. The novel concept of bidirectional low-temperature networks aims at recovering low-grade waste heat and is also referred to as 5th generation district heating, energy networks or cold district heating networks. A BLTN provides heating and cooling power with only one thermal network consisting of one warm pipe and one cold pipe. Since the operating network temperature (10 – 20 °C) is close to the ambient temperature, heat losses are kept to a minimum. In buildings, heat pumps are installed, which raise the temperature to the supply temperature of the building’s heating circuit. For cooling, either chillers or heat exchangers which enable direct cooling with the cold line of the BLTN are installed. Waste heat from chillers or direct cooling can be used as heat source for heat pumps. If, in one building, heating and cooling demands occur at the same time, these thermal demands can be balanced directly within the building (intra-building balancing). This reduces the thermal energy that needs to be supplied by the BLTN. In addition, heating and cooling demands can be balanced between buildings (inter-building balancing): Waste heat from chillers or direct cooling in one building is then reused by heat pumps in other buildings. Only residual loads that are not balanced within the network have to be covered by central supply units (energy hubs). The extensive use of heat pumps and chillers strengthens the coupling between the electricity and the heating sector and, thus, supports the integration of renewable energies in the electricity grid.
BLTNs are increasingly investigated in recent literature: Buffa et al. [2] provide an extensive review on 40 pilot projects across Europe in which BLTNs have been realized. Brange et al. [3] show the enormous potential of waste heat recovery in urban district. For a district in Sweden, they estimate that 50 – 120 % of the total annual heat demand could be met by waste heat sources. The exergy efficiency of BLTNs is investigated by Pass et al. [4]. They find that a BLTN is more efficient compared to an individual supply if there is at least 1 unit of cooling per 5.7 units of heating energy. Bünning et al. [5] developed an agent-based control for BLTNs using a dynamic simulation model. Also for controlling BLTNs, Vivian et al. [6] present a MILP formulation embedded in a MPC framework. Ruesch et al. [7] developed a simulation model for BLTNs using the software Polysun. In their study, they identify a lack of established design guidelines for BLTNs. They highlight three major fields that need to be addressed in future works: At the design stage, the network topology and pipe sizing can be optimized. On the building level, the selection and sizing of the energy conversion units is an important design task. At the operation stage, the optimal dispatch of all components in the district must be controlled efficiently. Due to the mutual heat exchange between buildings, the optimal design of building energy systems substantially depends on the waste heat potential of other buildings in the district. Consequently, planning methods for single buildings are not sufficient and provide non-optimal solutions. Instead, holistic approaches considering the district as a whole are better suited. Designing all energy conversion units of an entire district holistically is a challenging and complex task. To address this problem, we present a novel approach based on mathematical optimization. For this purpose, all energy systems of the buildings as well as a central supply unit are modeled within one linear program (LP). In Section 2, we describe the LP formulation in more detail. The results of a case study are presented in Section 3. Finally a conclusion and outlook is provided in Section 4.

2. Methodology

In this section, we describe the LP formulation and the underlying assumptions. As objective function, we consider total annualized costs. These include annualized investment costs as well as operation and maintenance costs, gas and electricity costs, as well as revenues for power feed-in. For gas and electricity, we consider a working price as well as a performance price. The LP formulation aims at selecting and sizing an optimal subset of energy conversion units for each building and the central supply unit (energy hub). In the following subsection, we briefly describe the underlying superstructure of the LP for the energy hub and the energy systems of the buildings.

2.1. Optimization superstructure

In Fig. 1, the superstructures of the optimization model are depicted. The superstructure of the energy hub (Fig. 1a) comprises heat generating technologies (gas and electric boiler (BOI/EB), CHP unit), power generating units (CHP unit, Photovoltaics) and cooling technologies (compression chiller (CC), absorption chiller (AC) and cooling tower (CT)). The flexibility of the operation is enhanced by three storage technologies: heat storage (TES), cold storage (CTES) and battery (BAT). A connection to the gas and power grid is available. Excess power from the CHP unit or PV modules can be fed into the public power grid. For the storage units in the energy hub, we use a linear formulation presented by Kotzur et al. [8] that allows a seasonal operation of storages even for MILP formulations which are based on design days.

In buildings, basic heating and cooling technologies are available, as depicted in Fig. 1b: For heating, a heat pump, an electric boiler as well as a heat storage are included in the superstructure. For the heat pump, we assume a low supply temperature (which results in a large COP). Thus, the heat pump cannot charge the heat storage which operates at higher temperatures and, therefore, can only be charged by the electric boiler. For cooling, a compression chiller, cooling tower and heat exchanger for direct cooling with the cold line of the BLTN are available. The possibility of direct cooling depends on the operating temperatures of the BLTN. The cooling tower can only be operated if the ambient air temperature is below the return temperature of the cooling circuit in the building (including a driving temperature difference for the heat transfer).
For gas and electric boilers as well as CHP units and absorption chillers, we assume constant conversion efficiencies. The COPs of heat pumps and compression chillers in the buildings are calculated a priori for each time step based on the network temperatures. For this purpose, we use a COP model presented by Jensen et al. [9]. Likewise, the COP of the compression chiller in the energy hub is calculated based on the ambient air temperature. Due to the design day clustering, the peak demands of the clustered design days may be smaller than the peak demands of the unclustered annual time series. Therefore, we add further constraints which ensure that the installed heating or cooling capacity is at least as large as the peak heating and cooling demands of the unclustered time series.

For modeling the network, a global energy balance is formulated. The net heat flow from the BLTN to the buildings (or vice versa) has to be balanced by the energy hub. In this simplified approach, no thermo-hydraulic effects are considered. However, the two major losses, thermal and hydraulic, are considered in the model. Based on a heuristically designed network topology and pipe sizing, thermal losses can be calculated a priori since the fluid temperature is assumed constant in the BLTN and is prescribed for each time step. The thermal losses (or gains) are then calculated based on an assumed heat transfer coefficient for the heat flow from the fluid to the surrounding. The heat losses are added to the energy balance of the network. Similarly, hydraulic losses can be estimated a priori based on volume flow rates in the pipes which are derived from a first simplified optimization run.

2.2. Benchmark scenario: Individual HVAC systems in buildings
In order to evaluate the performance of the BLTN, we compare it to a supply system without BLTN. In this scenario, the heating and cooling demand is covered by individual HVAC systems in the buildings. For a valid comparison, we use similar technologies: For covering the heating demands, an air source heat pump, electric boiler and heat storage is available in the superstructure. For cooling, compression chillers and cooling towers can be installed. The same area of PV modules is available as in the BLTN scenario. We assume that PV power can be exchanged between buildings without losses or limitations.

3. Case study
We apply the optimization approach to a district with 17 buildings on a research campus in Germany for which heating and cooling demand time series have been monitored. The building stock comprises office buildings, laboratories and two data centers. The data centers account for 73% of the total cooling demand. The supply temperature of each building’s heating circuit is assumed 60 °C and the cooling...
supply temperature 16 °C. We prescribe a constant operating temperature of the BLTN: 14 °C in the cold pipe and 18 °C in the warm pipe. These temperature levels allow direct cooling in the buildings and avoiding the installation of compression chillers. Based on these temperature levels, the COP of the heat pumps in the buildings is 5.05. The available roof area for PV installation is assumed 5000 m². The volume of the thermal energy storages in the buildings is limited to 10 m³ and in the energy hub to 100 m³. The annual time series are clustered into 50 design days which results in a LP with 530,000 decision variables.

We evaluate the performance of the BLTN with economic and ecologic performance indicators. The total annualized costs for the heating and cooling supply with the BLTN amount to 370.9 kEUR/a. If the TAC are referred to the total heating and cooling demand, the specific heating and cooling costs are 22.61 EUR/MWh (costs for the installation of the BLTN are included). Fig. 2 shows the cost portions for the two scenarios. In the BLTN scenario, gas costs account for 130.8 kEUR/a, electricity costs for 18.9 kEUR/a. The annualized costs (investment and operation & maintenance) of the equipment in the buildings and energy hub are 241.3 kEUR/a, the network installation costs are 31.8 kEUR/a. Revenues from electricity feed-in amount to 51.9 kEUR/a. For the benchmark scenario with stand-alone HVAC systems, the TAC are 634.1 kEUR/a or 38.66 EUR/MWh. Here, the largest cost share are electricity costs, since the heating and cooling demand is predominantly covered by heat pumps and compression chillers.

![Figure 2: Cost comparison between the BLTN solution and stand-alone HVAC systems](image)

For the BLTN scenario, in the buildings, the heating demand is predominantly covered by heat pumps. Electric boilers and heat storages are used for covering peak demands. In total, 1.82 MW heat pump capacity is installed in the buildings, 0.58 MW electric boilers and 0.34 MWh heat storage capacity. For covering the cooling demand, 2.86 MW direct cooling capacity (heat exchanger capacity) are installed. In the data centers, cooling towers are installed (0.46 MW). Cooling towers allow to dissipate waste heat directly to the surroundings if the waste heat cannot be reused by other buildings and would then need to be recooled by the energy hub. Compression chillers are not installed. In the energy hub, a trigeneration system is optimal: For heat generation, a CHP unit with a rated electric power of 0.26 MW and a gas boiler with a rated power of 0.22 MW is installed. For cooling the BLTN, a compression chiller with a cooling power of 2.04 MW and an absorption chiller of 0.16 MW is optimal. The optimal peak capacity of the PV modules is 0.63 MW. No electric boiler or cooling tower is installed in the energy hub.

Substantial proportions of the heating and cooling demands are balanced within buildings and within the BLTN. In Fig. 3a, the heating and cooling demands are depicted for one year. Fig. 3b shows the thermal demands after the intra-building balancing which are covered by the BLTN. Within the intra-
building balancing 32.0% of the thermal demands are balanced. However, due to the low heat demand in the data centers, the peak cooling demand in summer remains almost unchanged. In the second stage, thermal demands are balanced within the BLTN (inter-building balancing). In this use case, 51.0% of the remaining demands can be balanced in this way. The thermal demands which are not balanced within the BLTN are shown in Fig 3c. These residual thermal demands are covered by the energy hub. Due to the thermal demand balancing, especially the base demand can be reduced substantially. The peak cooling demand in summer can only be reduced slightly.

The supply system with stand-alone HVAC systems causes 1266 t CO₂ emissions per year. In the BLTN scenario, CO₂ emissions amount to 559 t/a, which means a reduction of 56%.

Figure 3: a) Heating and cooling demands (after design day clustering), b) Thermal demands covered by the BLTN (after intra-building balancing), c) Residual thermal demands covered by energy hub (after inter-building balancing)

4. Summary and outlook
In this paper, we present a linear program for designing bidirectional low-temperature networks (BLTN). The presented approach selects and sizes the optimal energy conversion units for each building connected to the network and an energy hub. For a case study, we evaluate the optimal solution with respect to economic and ecologic indicators. In total, 32.0% of the heating and cooling demands are balanced within the buildings. Of the remaining thermal demands, further 51.0% can be balanced within the BLTN. Compared to stand-alone HVAC systems, the total annualized costs of a BLTN solution are 42% lower and 56% less CO₂ emissions are produced. Heating and cooling demands in the buildings are predominantly covered by heat pumps and direct cooling. The optimal energy hub is a trigeneration
system including a CHP unit, a compression and absorption chiller, a gas boiler as well as heat and cold storages.

The applicability of the developed linear program can be enhanced by adding further technologies such as geothermal heat pumps or solar thermal collectors. Moreover, further energy carriers such as hydrogen can be integrated into the energy hub, e.g. for on-site utilization of excess PV or CHP power if the connection to the public power grid is limited or not available. Innovative storage technologies, such as ice storages can be included into the superstructure as well.

In future work, the simplified modeling approach for the network (formulation of one global energy balance) has to be investigated further with the help of thermo-hydraulic simulations.

In the model, we assume that all buildings are connected to the BLTN. However, this assumption can result in sub-optimal solutions. Therefore, further (binary) decision variables could be integrated into the model in order to determine the optimal set of buildings that should be connected to the network and, on the other hand, the buildings that should be equipped with an individual HVAC system.

The LP can also be adapted for model predictive control (MPC) frameworks, especially due to the low computation times even for larger districts. For this purpose, the design variables are fixed, and more detailed operation constraints are added to the model formulation.

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