ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Bidirectional low temperature district energy systems with agent-based control: Performance comparison and operation optimization

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HIGHLIGHTS

- A concept for the operation optimization and control of low temperature networks is developed.
- The concept is based on a temperature set point optimization and agent-based control.
- It is validated using dynamic modeling and simulation in Modelica.
- It is compared to other heating and cooling technologies or control concepts in two scenarios.
- Results show significant energy savings when the control concept is used.

ARTICLE INFO

Keywords:
Low temperature network
District heating
Urban energy systems
Operation optimization
Modelica
Agent-based control

ABSTRACT

Bidirectional low temperature networks are a novel concept that promises more efficient heating and cooling of buildings. Early research shows theoretical benefits in terms of exergy efficiency over other technologies. Pilot projects indicate that the concept delivers good performance if heating and cooling demands are diverse. However, the operation of these networks is not yet optimized and there is no quantification of the benefits over other technologies in various scenarios. Moreover, there is a lack of understanding of how to integrate and control multiple distributed heat and cold sources in such networks. Therefore, this paper develops a control concept based on a temperature set point optimization and agent-based control which allows the modular integration of an arbitrary number of sources and consumers. Afterwards, the concept is applied to two scenarios representing neighborhoods in San Francisco and Cologne with different heating and cooling demands and boundary conditions. The performance of the system is then compared to other state-of-the-art heating and cooling solutions using dynamic simulations with Modelica. The results show that bidirectional low temperature networks without optimization produce 26% less emissions in the San Francisco scenario and 63% in the Cologne scenario in comparison to the other heating and cooling solutions. Savings of energy costs are 46% and 27%, and reductions of primary energy consumption 52% and 72%, respectively. The presented operation optimization leads to electricity use reductions of 13% and 41% when compared to networks with free-floating temperature control and the results indicate further potential for improvement. The study demonstrates the advantage of low temperature networks in different situations and introduces a control concept that is extendable for real implementation.

1. Introduction

1.1. Background and motivation

District heating systems have been used for space heating and domestic hot tap water since the 1880s. Since then the efficiency of these systems has been improved continuously and four different generations of district heating systems can be distinguished, differing in heat carrier, temperature levels, circulation systems and substations [1].

With respect to the four different generations of district heating systems, bidirectional low temperature networks (LTN) can be viewed as a fifth generation district heating and cooling system, as suggested by the European Commission [2]. They constitute an approach to further increase energy efficiency for heating and cooling of buildings by further lowering the fluid temperature in the networks to ambient temperature levels. The networks consist of two pipes. The warmer pipe has

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https://doi.org/10.1016/j.apenergy.2017.10.072
Received 31 July 2017; Received in revised form 2 October 2017; Accepted 23 October 2017

temperatures between 12 °C and 20 °C, while the cold pipe has 8–16 °C. Buildings equipped with heat pumps, chillers or direct cooling and individual circulation pumps are connected to both lines. In the case of a heating demand, the circulation pump of the building withdraws water from the warm line, uses it in a heat pump to reach temperatures suitable for space heating, and then discharges the cooled water to the cold line. In case of a cooling demand, the system works in the other direction. Depending on the heating and cooling demands of the connected buildings, the fluid flow in the network can change direction. The total difference between heating and cooling flows needs to be balanced by external sources, e.g. central heat pumps and chillers, solar thermal plants or seasonal storage facilities.

The concept is in the early stages of research and development. There is theoretical proof of the concept based on thermodynamic analysis [3]. Furthermore, there are at least eight demonstration projects (unidirectional and bidirectional) in operation or under construction (e.g [4–6]). Research regarding the optimal design in terms of diversity of cooling and heating loads has also been conducted lately [7].

Despite the previous efforts, there is a significant need for further research in multiple areas. It appears that no publications about control and operation optimization of LTN are available. There is proof that LTN are beneficial in terms of exergy efficiency, but the full potential has not been exploited yet. Moreover, there is a lack of understanding of how to integrate and coordinate multiple source networks in which individual so called “prosumers” can participate in heat and cold supply. Furthermore, there is only limited insight into the potential advantages a bidirectional LTN has over other technologies in different scenarios. To address these open questions is a crucial prerequisite for the future of sustainable heating and cooling systems through LTN technology.

Therefore, this study introduces, to the authors’ knowledge, the first approach to operation optimization of low temperature networks. The approach consists of an optimization of the network temperature, which is the main influence on energy costs of such networks, and a control concept based on a market-based multi-agent system. With proper multi-agent control the electricity consumption of the heat pumps and chillers in the network can be lowered. Furthermore, the agent system allows the integration of multiple heat and cold sources and energy storages into the network, which makes it a practical approach for smart-grid-like decentral networks. The approach is verified with the help of dynamic simulations based on Modelica, for which the authors implemented the necessary models [8,9] and the agent-based control system [10]. The case study examines two district scenarios, one of which is situated in the USA and one in Germany, and compares low temperature networks to other heating and cooling options. The results allow an insight into the behaviour of low temperature networks, present a proof of concept for the control approach and provide a quantification of energy cost savings through the use of low temperature networks instead of conventional heating and cooling technologies.

1.2. Previous work on low temperature networks

There is only a small number of peer-reviewed scientific work published in the field of bidirectional LTN. To give a complete overview of the topic, also reports on pilot projects by construction companies and other non-scientific sources are cited in the following.

One of the earlier examples of an LTN as described in this study was introduced in [11] as a plan to create a district heating and cooling system for a developing area in Visp, Switzerland. The unidirectional grid uses waste heat from a sewage of a chemical plant as a heat source and de-centralized heat pumps are used in the individual residential buildings to lift the temperatures sufficiently high to operate floor heating systems. Ref. [5] presents an evaluation of the system installed in Visp. Completed in 2008, it has a total thermal capacity in heating of 3.6 MW and is competitive with other technologies in terms of cost of operation at a domestic fuel oil price below $0.9/lt.

In [4], an LTN for heating and cooling of parts of the campus of ETH Zürich is proposed. In order to reach the goals for a 2000-Watt-society [12], besides other measures, plans for a grid consisting of multiple ground heat storages, a geothermal field and de-central heat pumps are presented. Details on the progress can be found in [6].

Besides introducing the bidirectional concept, [13] makes several contributions to the topic of LTN: the author highlights the advantage of LTN in urban areas, where it is difficult to install heat pumps with individual ground or groundwater heat exchangers for residential buildings. Moreover, heat and cold demand should be of a similar size in the ideal case. The role for the operator of the system is to keep the temperatures at a sufficient level for cooling and heating and to balance the energy flows over the year in all storage facilities. It is further pointed out that LTN are modular and can be started as small projects that can be scaled up later on. A measure to further decrease operation costs could be the provision of grid services, as the used heat pumps constitute groups of high electrical capacities.

In [14], Sulzer examines the possibility of integrating solar thermal panels into LTN. The author states that integration of such systems is favourable in the case of seasonal heat storage as the demand for heat is higher in winter, but the production from solar thermal panels is high in summer. In [15], Sulzer et al. introduce different typologies of grids in terms of number of pipes between one and four. While the previously introduced bidirectional networks operate with two pipes at different temperature levels, third and fourth pipes with higher or lower temperatures are possible in order to use direct floor heating without a previous temperature lift via a heat pump, for example. Moreover, Sulzer now distinguishes between unidirectional and bidirectional grids in terms of mass flow and energy flow. A grid can be unidirectional in mass flow but bidirectional in terms of energy flow (e.g. in the case of Visp). Additionally, he presents several problems and unanswered questions related to the networks: So far, technological expertise is limited to a very small group of people. There are no standardized ways to calculate the cost of such a network for planners who were not involved in the pilot projects. Furthermore, the operation of LTN has not been optimized yet.

In [16], two different types of ownership for LTN are suggested. Bigger LTN could be owned by a grid operator, similarly to electrical grids or common district heating grids. Smaller grids could be owned and operated by the real estate owner. An example of a real-estate owned system in Chur, Switzerland, is given. A comparison between investment cost for a centralized heat pump system and an LTN is made and the LTN is found favourable. Furthermore, a comparison between yearly energy costs for the LTN in Chur and the local heating system installed before is made. A reduction of 62% of the annual energy costs could be observed.

Although focusing on heating grids with higher supply temperatures, Li et al. [17] point out that the development of future district heating grids will move away from hierarchical, fossil-based, large-scale structures towards future decentralized, multiple renewable and waste-heat-dominated small structures. Moreover, they postulate the idea that individual “prosumers” in the network who have the capacity to produce surplus heat from building installed solar collector, heat pump, micro-CHP and individual thermal storage, should be able to participate in the future grids. Pietra et al. [18] investigated the benefit of a grid connection for owners of solar thermal panels. The bidirectional grid operates as a virtual heat storage for the prosumer with the effect that the collectors can be operated throughout the whole summer instead of being stopped because of low heat demand during that period. Results show that the solar collector is able to supply more than 100% of the total yearly heat demand for an apartment when connected to the grid in comparison to 27% before, which leads to an operational cost reduction of 60%.

Gautschi [6] presents long-term experience with LTN. According to