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A feasibility and performance assessment of a low temperature district heating system — A North Japanese case study

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ABSTRACT

This paper presents a high spatial resolution based method for design and operation of a low temperature district heating system and evaluates its feasibility and energy and exergy performance through case comparison. Selected case area is existing district in North Japan. The district heating system design and operation follows a bottom-up approach. The study scope takes into account the demand side, distribution and supply side where biomass CHP (combined heat and power) plant is selected as main supply source. Radiating floor heating system model is used to estimate building temperature requirement. Results indicate that low temperature heating is infeasible for non-residential buildings in North Japan at high loads. Improving building insulation decreases heating quality demand considerably. Low temperature district heating performs better than medium temperature, especially in terms of exergy efficiency, however requires a bit larger pipe diameter indicating cost trade-off between installation and operation cost. Implementing cascade configuration based on quality level of building energy demand results in highest system performance. Lower network temperature provides least net primary energy consumption primarily due to higher electricity generation of CHP plant. This transcends to favourable system exergy efficiency of low temperature operation due to high quality of electricity, increasing the exergy of the product.

1. Introduction

The transition of the current heat supply system paradigm is facing challenges of both quantitative as well as qualitative nature. In relatively cold climates, space heating accounts for large share of building sector's annual energy demand. In Tohoku region for example, North Japan, space heating and hot water account together for 66% of the building sector's total energy demand on annual basis [1]. The heat supply is mainly being provided by fossil fuels or electricity, which brings to the qualitative challenge as these are high quality energy sources used to supply low quality energy demand such as space heating and hot water [2]. With countries striving to reduce their GHG emissions and increase their energy independence, this shows that the transition of the heat supply system requires considerable attention.

Studies have shown that by changing the approach for heat supply system design, considerable performance improvement of energy supply systems to buildings can be achieved. By averting from the current resource driven design approach, where the quality level of different energy end-use demands is largely remiss, to a more demand driven integrated supply system design, a proper use of exergy may be realized. This can be achieved via use of energy quality management approaches. Zubiaga et al. for example demonstrated the added value of exergy in building heat supply system design for achieving reduced primary energy source consumption [3]. In similar way, Goncalves compared several building based heat supply systems under different climate conditions, further emphasizing the importance of reducing the exergy consumption for building heat demand [4]. These studies are largely based on previous research of some of the originators of exergy approach application for building heating systems. To mention did Schmidt develope a bottom-up approach for system input exergy minimization through input output analysis, mainly focussing on heating and cooling systems [5]. Shukuya has furthermore developed extensive and robust base of exergy theory and calculation of HVAC and lighting systems for buildings [6]. For extensive list of exergy based studies of buildings I refer to review paper of Hepbasli [7]. As exergy is a pivotal part of these energy quality management

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approaches, the research community refers to them as “low exergy design” (or LowEx design) and building energy supply systems subject to low exergy design a “low exergy systems” [8]. The low exergy design approach has however mainly been applied to single buildings with building boundary as system boundaries [9]. Applying low exergy design approach on community has however also a great potential as has been explained in Ref. [2].

DHS (District heating system) is a proven technology for supplying heat from centralized sources to buildings within a community. Heat sources have been increasingly moving from fossil fuel combustion to local waste heat, biomass and even geothermal sources and for some countries district heating systems have played a key role of helping energy system transition towards increased sustainability. Denmark and Sweden have for example become especially successful in that regard as demonstrated by Chittum et al. [10] and Di Lucia [11]. The next or 4GDHS (4th generation district heating system) (also referred to as LTDHS (low temperature district heating system)) is considered to increase the potential impact of DHS towards sustainability even further as thoroughly explained in the concept paper by Lund et al. [12]. Hypothetically the low network supply temperature improves the network performance, makes local renewable and waste heat and heat pump integration easier and enables cascade utilization and other synergy effect through smart thermal network operation. Table 1 enlists the typical temperature range of LTDHS compared to medium temperature, high temperature and steam based district heating systems along with other key differences.

Few studies have been carried out on LTDHS in recent years but most of them have been studied within the context of low energy buildings, as reduced space heating demand is considered as a prerequisite for 4GDHS deployment due to physical and thermal limitation of the radiation heating systems. Li et al. conducted energy and exergy analysis for a small DHN (district heating network) and found that the energy and exergy performance of low temperature operation is considerably higher compared to medium temperature operation [13]. The study of Dalla Rosa et al. concurred with the superior energy performance of low temperature operation of a DHN however with an increased capital investment required for the network pipeline [14]. It also found the local lower economic feasibility limit for LTDHS in terms of linear heat density. Tol et al. studied the physical configuration of district heating system in terms of pipe network dimension, network layout and substation configuration in a low energy district heating scheme [15]. They found that including buffer tank at each substation leads to favourable pipe dimension and heat loss. The results also revealed that tree structure network layout compared to loop layout results in less heat loss. Another study by Tol et al. demonstrated that by boosting the network supply temperature at peak periods in a low temperature operation scheme leads to reduction in mass flow, reduced heat loss and lower equivalent pipe diameter compared to fixed supply temperature, given a short duration of the cold period [16]. These studies mainly focus on the distribution network design while taking into account different building installation configuration. They also assume compatibility between low temperature heating system and existing buildings in terms of thermal comfort.

In addition to Li et al. others have studied the thermal inefficiencies of district heating systems using exergy analysis. Comakli et al. proposed calculation method for evaluating exergy losses in a district heating network dividing the losses depending on source; heat loss, hot water transportation and heat transfer in heat exchanger [17]. Multiple exergy analyses have been conducted on geothermal district heating systems. Oktay et al. found for example the main exergy waste of a real geothermal district heating system, showing largest exergy destruction occurring in primary heat exchangers [18]. Alkan et al. did also an exergoeconomic analysis on a geothermal district heating system, coupling cost to exergy for assessing the cost feasibility of thermodynamic improvement potential of system components [19]. By comparing different substation configurations in connection with district heating system, Torio et al. found that minimizing the supply and return temperature of a district heating system results in highest exergy performance and that supply temperatures have larger impact on the exergy performance compared to the return temperature [20]. Gong et al. conducted exergy analysis of Swedish and Danish district heating systems, considering just the network supply and return temperatures, and found that about two thirds of the exergy supply is currently being lost in the distribution network and building substations [21]. They also stress the potential of reducing the exergy factor of the distribution network, closer to the heat demand level, by achieving building heat load reduction. Baldvinsson et al. have also demonstrated the thermoeconomic advantages of district heating system over fossil fuel based distributed heating generation and a thermodynamic improvement potential of the district heating system by reducing the operation scheme from medium to low temperature setting [22].

Researchers have also focused their work on exergy matching of supply sources and demand at a community level. Sanaei et al. conducted an analysis of a community scale energy supply system, using exergy matching diagram to optimize the cascade potential of enthalpy flow originating from fossil fuel power plants [23]. Similarly did Kilkis present an exergy matching tool, “The Rational Exergy Management Model”, that attempts to reach net-zero exergy supply at a district level, resulting in primary energy source consumption and CO_2 emission reduction [24]. Lu et al. have conducted a series of studies proposing a multi-objective optimization model for district energy system design, showing the trade-off between exergy efficiency, lifecycle cost and lifecycle CO_2 emissions. In Ref. [25] they demonstrate the positive correlation between system lifecycle cost and system exergy efficiency and further show the positive effect of increased system exergy efficiency on lifecycle CO_2 equivalent in Ref. [26]. These studies do however neglect accurate presentation of the distribution network, binding together the supply and demand side. This indicates a potential gap in the literature of exergy based district energy

Table 1
Types of district heating systems and some key characteristics.

	Steam	HT	MT	LT
Generation	1st	2nd	3rd	4th
Peak period	1880–1930	1930–1980	1980–2020	2020–2050
Supply/return temperature	>100 °C	120/70 °C	90/50 °C	60/30 °C
Heat carrier	Steam	Pressurized hot water	Pressurized hot water	Cold water
Pipe type	In-situ steel pipe	In-situ steel pipe	Pre-insulated steel pipe	Pre-insulated flexible pipe
Dominant heat production	Coal steam boilers	Coal and oil boilers and CHP	Waste and biomass CHP and fossil fuel boilers	Waste heat and renewables

Adopted from Lund et al. [12].