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5th Generation District Heating: A novel design approach based on mathematical optimization

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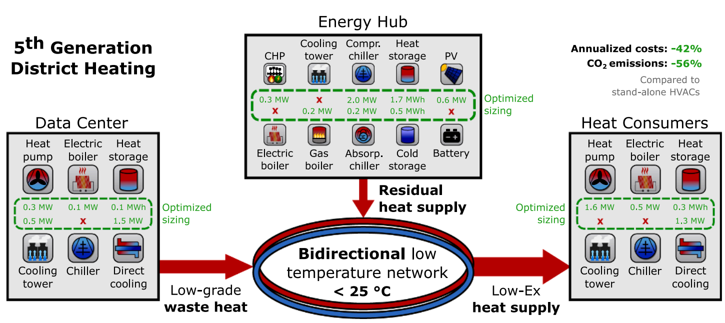
HIGHLIGHTS

- Linear Program for designing bidirectional low temperature networks.
- Holistic sizing approach for all building energy systems in a district.
- Performance evaluation with economic, thermodynamic and ecologic indicators.
- Comparison with stand-alone HVAC systems.
- Bidirectional low temperature network result in substantial energy and cost savings.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a novel design methodology based on Linear Programming for designing and evaluating distributed energy systems with bidirectional low temperature networks (BLTNs). The mathematical model determines the optimal selection and sizing of all energy conversion units in buildings and energy hubs connected to the BLTN while minimizing total annualized costs. The optimization superstructure of building energy systems comprises heat pumps, compression chillers, heat exchangers for direct cooling, cooling towers and thermal energy storages. The design approach is applied to a real-world use case in Germany and the BLTN performance is compared to a reference case with individual HVAC systems. The BLTN concept shows a cost reduction of 42% and causes 56% less CO_2 emissions compared to individual HVAC systems.

1. Introduction

With 50% of final energy consumption, heating and cooling is the largest energy sector in Europe [1]. While the heating demand is expected to decrease, the cooling demand in buildings will increase substantially in the upcoming decades [2]. The task of an emission-free supply of heating and cooling energy is challenging, especially in urban areas: Space is a very limited resource and noise emissions should be kept to a minimum. An energy supply by individual supply units in buildings is therefore not satisfying. Instead, district heating and cooling (DHC) gains more importance. DHC networks enable an efficient energy supply while reducing primary energy demands as well as local emissions [3]. In order to increase the efficiency of thermal networks, a tendency towards lower operating temperatures is observed [4]. Lower network temperatures reduce thermal losses and enable the integration of low-grade waste heat and renewable heat sources ([5,6]).

The latest innovation in district heating are 5th Generation District Heating and Cooling networks. In the following, a brief literature review on this technology is provided and relevant gaps for this work are identified.

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Nomenclature

Abbreviations

AC	Absorption Chiller
BAT	Battery
BES	Building Energy System
BLTN	Bidirectional Low Temperature Network
BOI	Gas Boiler
CC	Compression Chiller
CHP	Combined Heat and Power
CT	Cooling Tower
CTES	Cold Thermal Energy Storage
DHC	District Heating and Cooling
EB	Electric Boiler
EH	Energy Hub
FOM	Figure of Merit
DRC	Direct Cooler
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
LP	Linear Program
MILP	Mixed-Integer Linear Program
PV	Photovoltaics
SOC	State of Charge
STC	Standard Test Conditions
TAC	Total Annualized Costs
TES	Thermal Energy Storage

Indices and Sets

$b \in \mathrm{B}$	Buildings
$d \in \mathrm{D}$	Design days
$t \in \mathrm{T}$	Time steps
$y \in \mathrm{Y}$	Days of the year

Variables

A	Roof area
cap	Device capacity
C	Annualized costs
E	Exergy
G	Gas energy
I	Investment
P	Electric power
Q	Thermal energy
R	Annualized revenue
S	State of charge
W	Electric energy

Parameters

β	Heat ratio
η	Efficiency
ρ	Density
$\sigma(y)$	Design day assignment function
ϕ_{loss}	Loss factor
τ	Minimum charging/discharging time
a_{inv}	Capital recovery factor
c	Specific costs
c_{p}	Specific heat capacity
e	Specific CO_2 emissions
COP	Coefficient of performance
f	Figure of merit
f_{om}	Cost share for operation & maintenance
i	Specific investments
kA	Thermal transmittance
N	Number of decision variables
p	Specific price
PEF	Primary energy factor
r	Specific revenue
R_{gas}	Energy grade function of natural gas
s	Proportion of storage capacity
T	Temperature
V	Storage volume
w_d	Design day weight

Sub- and Superscripts

el	electric
ex	exergy
c	cooling
cap	capacity
ch	charge
dch	discharge
dem	demand
h	heating
init	initial
max	maximum
min	minimum
netw	network
nom	nominal
sol	solar
sup	supply
ref	reference
res	residual
ret	return
th	thermal
tot	total
w	water

1.1. 5th Generation District Heating and Cooling

The latest stage in the development of DHC systems are *5th Generation District Heating and Cooling* (5GDHC) networks ([7,8]). In literature, these networks are also referred to as *Bidirectional Low Temperature Networks* ([9–12]), *Cold District Heating Networks* (in German *Kalte Nahwärme*) ([13,14]) or *Anergy Networks* ([15–17]) (in German *Anergienetze*). In this study, they are referred to as *Bidirectional Low Temperature Networks* (BLTN). The general concept of BLTNs is depicted in Fig. 1. Heating and cooling consumers are connected to a thermal network which consists of a warm and a cold pipe. The temperature of the fluid in the warm pipe is around 5–10 K higher than the temperature in the cold pipe. The temperatures in both pipes are close to the surrounding (5–30 °C), which keeps heat losses to a minimum. In order to raise the temperature level for space heating or domestic hot water, buildings are equipped with heat pumps. Heat pumps use water from the warm pipe as heat source. Cooled water from the evaporator is then discharged into the cold pipe. Likewise, chillers use the network as heat sink. They take water from the cold pipe and discharge the heated fluid into the warm pipe. Thus, the flow direction of the water in the network can change over time in each segment of the network and only depends on the operation of the decentralized pumps