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Economic assessment of alternative heat decarbonisation strategies through coordinated operation with electricity system – UK case study

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HIGHLIGHTS

- A whole system approach is applied to analyse alternative heating strategies.
- Hybrid heat pump and gas boiler shows significant advantages over other options.
- The competitiveness of district heating is sensitive to heat density.
- All district heating is deployed in urban areas in the optimal heating strategy.
- Alternative heating strategies have significant impacts on the electricity system.

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ABSTRACT

Electric heat pumps (HPs), hybrid heating technology and district heating networks (DHN) are the main low-carbon heating technologies that can deliver the ambitious carbon reduction target in the UK. The optimal design of the heating system on a national scale to maximize the economic benefits regarding both investment cost and operation cost while satisfying the carbon target remains an open question. This paper aims to compare the economic advantages as well as the associated impacts on the electricity system under the full deployments of ASHP (air source HP), hybrid HP-Bs (ASHP and gas boilers) and DHNs. To do so, a novel whole-system approach is applied with the explicit consideration of the coordinated operation between heat and electricity system. The optimized strategy for heat sector decarbonisation is also demonstrated, providing an outline of the optimal deployment for different heating technologies in terms of their penetrations and deployed areas. The UK case study suggests the significant economic advantage of the hybrid HP-B over the other two heating technologies, while DHN may play an important role in urban areas under the optimized heat decarbonisation strategy. The results also clearly demonstrate the changes on the electricity side driven by the different decarbonisation strategies in the heating system.

1. Introduction

The heat sector accounts for approximately half of the total energy consumption in the UK. In order to meet the target of 80% carbon reduction by 2050, alternative heating technologies are required to replace gas boilers that currently predominate in the UK. Electric HPs, hybrid heating technologies and DHNs are promising low-carbon heating technologies that can potentially deliver the carbon target [1–3], whereas the comparison of their economic competitiveness, which is crucial for their large-scale deployment, remains unknown. Due to the interactions between heat system and electricity system, the investment strategy of various heating technologies can bring significant impacts to electricity sectors. This leads to the need of the joint optimisation of heat and electricity system investment. Given that the lack of flexibility in the electricity system is a key factor that limits the integration of RES [4], heat systems can potentially deliver substantial amount of flexibility by providing various balancing services and support peak demand management [5]. As presented in [6] and [7], district heating can alleviate the curtailment of RES through coordinated operation of multiple components in heat networks (e.g. CHP, TES, electric boilers, etc.). Reference [8] demonstrates an operating model of multiple heat plants feeding heat to DHNs, while the advantages of the deployment of industrial-sized HPs in DHNs are presented in [9–11]. In regard to end-use heating technologies with low-carbon potentials, research [12–14] are focused on the analysis of hybrid heating technologies on the consumer side, with the potential to connect HPs, gas

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Nomenclature

Acronyms

ASHP	air source heat pump
CAPEX	capital cost
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CHP	combined heat and power
COP	coefficient of performance
DHN	district heating network
DN	distribution network (electricity)
EGB	end-use gas boiler
ETES	end-use TES
HP	heat pump
IHP	industrial heat pump
IGB	industrial gas boiler
ITES	industrial TES
LG	low carbon generation
OPEX	operation cost
OCGT	open cycle gas turbine
RES	renewable energy source
TES	thermal energy storage

Constants

η^s	storage efficiency of TES
τ	minimum fully charging time from empty
A	size of area of representative districts
$\overline{CO2}$	CO2 emission target
d^h	heat demand
d^{nhp}	non-heat electricity demand
N^c	number of consumers
N^{ra}	number of different representative districts
$\bar{s}^{in}$	maximum heat charging rate of TES
T^a	ambient temperature

Variables

α^{hn}	penetration of DHN in different representative districts
μ	number of synchronized units
ω^d	penetration of district heating systems
ω^e	penetration of end-use heating systems
$CO2^g$	CO2 emission from generation
$CO2^b$	CO2 emission from gas boilers
COP^a	coefficient of performance for ASHP
C^{hn}	capital cost of heat network per unit length
cap^f	transmission line capacity
cap^g	generation capacity
cap^h	capacity of various heating assets
d^p	total electricity demand
$\bar{d}$	peak load in a given distribution network
h^b	heat output of gas boilers
h^d	heat provided by district heating plants/devices
h^e	heat provided by end-use heating appliances
p^g	electricity output of various generation
re	electricity output of RES generation
rsp^g	response service provided by various generation
rsp^h	response service provided by various heating technologies
s^e	stored energy content of TES
s^{in}	heat charging rate of TES
s^{out}	heat discharging rate of TES

Functions

$C_{op}^b(\cdot)$	function of operation cost for gas boilers
$C_{op}^g(\cdot)$	function of operation cost for generation
$C_{inv}^g(\cdot)$	function of investment cost for generation
$C_{inv}^f(\cdot)$	function of reinforcement cost for transmission system
$C_{inv}^h(\cdot)$	function of investment cost of heating assets
$C_{inv}^{hn}(\cdot)$	function of investment cost of heat networks
$C_{inv}^{dn}(\cdot)$	function of reinforcement cost of distribution networks
$l(\cdot)$	function of the length of heat networks
$\underline{srp}(\cdot)$	function of requirement of frequency response

Sets

B	set of gas boilers
D	set of representative district types (including urban, sub-urban, semirural and rural districts)
DN	set of distribution networks
F	set of transmission corridors
G	set of generation technologies
H_d	set of district heating assets
H_e	set of end-use heating assets
R	set of regions
T	set of operating snapshots

boilers and resistive heating devices through smart control. The economic and operational performances of different hybrid heating technologies are elaborated in [13], manifesting significant economic advantages through the deployment of hybrid electric HPs and gas boilers (Hybrid HP-B). Due to the thermal inertia of pipework, DHNs can provide flexibility to the electricity system [15]. Moreover, supported by TES which is characterized with significantly lower capital cost than electricity storage, the value of DHNs can be further enhanced through coordinated operation with electricity systems [16]. Similarly, the performance of TES supporting end-use heating appliances is discussed in [13]. Previous research regarding the planning of DHNs is mainly focused on the local level [17–19], while the national level infrastructure is barely considered. A whole-system approach is presented in [20] to optimize the investment of the electricity system where only electric HP is considered for decarbonizing the heat sector. In this context, this paper applies an integrated electricity and heat system investment model to assess the economic performance of various heat decarbonisation strategies. Compared to the previous developed model for multi-energy system planning (e.g. Balmoral model), the proposed model can cover both local district and national level infrastructures while taking account of the impact of reduced electricity system inertia on the frequency response requirements. Moreover, carbon emission restrictions can also be considered to investigate the economic performance of alternative heating strategies under specific carbon scenarios.

A set of comprehensive case studies are carried out to (1) compare the annual system cost coving multiple sectors under the heating strategies of HP-only (electric HP is the only option of heat provision), hybrid HP-Bs and DHNs; (2) analyse the impact of different heating strategies on the electricity system; and (3) present the optimized portfolio of heating technologies to achieve the decarbonisation.

2. Characteristics of different heating technologies

At present, around 80% of the households in the UK are using natural gas boilers for residential heating. As most of the residential gas boilers are still in operation, it is challenging for customers to decommission their gas boilers and reinvest in new heating equipment. Hybrid heating technologies can help alleviate the pressure of large investment