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Integrating a thermal model of ground source heat pumps and solar regeneration within building energy system optimization

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HIGHLIGHTS

- Short term heat pump operation results in cooling of the ground.
- Solar regeneration increases the ground temperature due to storage of heat.
- Ground temperature reduces significantly in 20 years due to annual heat imbalance.
- Solar thermal collectors and borehole heat exchangers mainly affect investment costs.
- Window retrofitting reduces the total CO_2 emissions by 27.3% at no additional costs.

ABSTRACT

The optimal design and operation of an integrated building energy system consisting of the renewable energy technologies such as ground source heat pumps (GSHPs) and solar thermal collectors, etc., is an important problem to be addressed. This paper describes a methodology for the optimization of a building energy system including a detailed thermal model of a borehole heat exchanger based GSHP. The novelty of this model is that it enables the study of dynamic temperature changes within the ground during operation. Furthermore, a model of solar thermal collectors is also included, which enables the study of solar regeneration of the ground in the short and long-term. Additionally, seven scenarios of building envelope retrofit are evaluated alongside optimal system design solutions. The methodology uses a bi-level multi-objective optimization approach, which consists of a genetic algorithm at the design level, and a mixed integer linear program at the operation level, in order to minimise the total costs and CO_2 emissions. The methodology is applied to a single-family residential building in Zurich, Switzerland, in order to demonstrate its application and analyse the design and operation of the system, with special attention to the GSHP. The results indicate that in the short-term, the ground temperature reduces considerably, to almost 5 °C as compared to the initial temperature of 11.5 °C. Furthermore, solar regeneration due to excess heat in summer increases the temperature back above initial temperature. However, due to due to insufficient regeneration in the long-term, the ground temperature drops consistently to almost 4 °C at the end of 20 years of operation. On the demand-side, window retrofitting results in a 27.3% reduction in the total CO_2 emissions at almost no additional costs. Retrofitting the whole building including windows, walls, roofs, and floors, is a CO_2 optimal solution however, performs worst in terms of cost optimality.

1. Introduction

The collective political will towards combating climate change, has led governments to encourage CO_2 emissions reduction, and energy efficiency improvements in the building sector. The Energy Performance of Buildings Directive (EPBD) of the European Union (EU), recommends supply-side building interventions such as the use of decentralized renewable energy systems for electricity, hot water, and heating services [1, Article 6]. It also proposes appropriate dimensioning, installation, and control of building systems, in order to optimize the energy use within buildings [1, Article 8]. Furthermore, demand side building interventions such as retrofitting of the building envelope are also recommended [1, Article 7]. In Switzerland, the energy strategy 2050 is the political basis for achieving long-term goals towards the energy transition, and recommends similar measures through its building refurbishment program [2]. The above-mentioned

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Nomenclature

Acronyms

GA	genetic algorithm
MILP	mixed integer linear programming
GSHP	ground source heat pump
PV	photovoltaic
ST	solar thermal
HP	heat pump
BHE	borehole heat exchanger
TES	thermal energy storage
GB	gas boiler
EH	electric heater
DHW	domestic hot water
SH	space heating
SC	space cooling
NR	no retrofit
WL	window limit
WT	window target
FL	façade limit
FT	façade target
WBL	whole building limit
WBT	whole building target
ELDC	error in load duration curve

Subscripts/superscripts

L	load side
S	source side
b	borehole wall
o	far-field
mf	mean fluid
ref	reference/rated conditions
s	steady state
in	inlet
out	outlet
IAM	incident angle modifier
regen	regeneration
a	ambient
h	hot flow
c	cold flow
loss	flow related to heat losses
t	time
l	layer

Symbols

$\dot{q}$	heat energy flow [W]
$\dot{p}$	power flow [W]
T	temperature [K]
$\dot{m}$	mass flow [kg/s]
g	dimensionless temperature response (g-function) [–]
r	radius [m]
t	time [s]
k	thermal conductivity [W/mK]
L	length [m]
a, b	heat pump equation fit coefficient [–]
R	thermal resistance [K/W]
y	binary variable [–]

policy measures will likely push towards both, supply-side as well as demand-side building interventions, which provide promising options for achieving the envisioned targets.

Ground source heat pumps (GSHPs) and solar thermal collectors are commonly used renewable energy technologies, which can be easily integrated within residential buildings. These are ideal for providing services such as space heating, cooling, and domestic hot water (DHW), and have considerably lower CO_2 emissions as compared to their fossil fuels counterparts [3]. Typically, GSHPs consist of vertical borehole heat exchangers (BHEs) used to extract heat from the ground. Long BHE length improves heat extraction, and results in higher coefficient of performance (COP) of the heat pump (HP), however, at high investment costs. On the other hand, short BHE lengths cool the ground due to excessive heat extraction, resulting in lower COP and higher operational costs. Solar thermal (ST) collectors when combined with GSHPs in the form of a hybrid system can solve the problem of ground cooling. Surplus solar heat, especially during summer, can be injected into the ground [4] in order to elevate the ground temperature back to the initial level or higher, preparing it for the upcoming heating season in winter. This process is referred to as seasonal solar regeneration. In the long-term, seasonal solar regeneration of the ground can significantly improve the performance of the HP [5] and lower the required BHE length, thereby reducing the overall investment costs and embodied emissions. In the short-term, it may increase the COP of the HP, thereby reducing the operation costs and CO_2 emissions. From a modelling perspective, the integration of a detailed thermal model of BHEs, GSHPs and ST collectors, within a building's energy system optimization can help in analysing the dynamic changes in the ground temperature and the effect of solar regeneration on it.

GSHP and ST collectors provide heat more efficiently at lower temperatures of around 50–60 °C as compared to conventional fossil fuel based technologies. However, the space heating distribution system may require higher temperature, around 70–80 °C, especially in buildings with old construction. Furthermore, DHW must be supplied above 50 °C, to avoid health problems related to legionella growth. Therefore, auxiliary technologies such as natural gas boiler (GB) may be required, which can prepare water at higher temperatures. Other alternatives are oil/biomass boiler, electric immersion heaters, etc. Electric heaters (EHs) particularly, have lower investment costs as compared to HPs; therefore, it may prove to be a better method for conversion of electrical power to heat in terms of total costs and CO_2 emissions. This is especially true, in the case of excess power available from the PV panels. Additionally, a stratified thermal energy storage (TES) tank can be used for balancing the intra-day mismatch between solar energy supply and demand. Furthermore, the stratified TES can be useful for the optimal management of the different temperature levels of energy supply and delivery. The design of such an energy system entails the selection and sizing of each of the technologies to fulfil the building energy demand. These design decisions can be made through the minimisation of the total annual costs, which include investment and operation costs, and CO_2 emissions, which include embodied and operating emissions. This can be achieved through an integrated optimization model that calculates optimal design an operation of such a system, given the technology-specific and systemic constraints.

On the demand-side of the possible building intervention measures, building envelope retrofitting/replacement can substantially lower the building heating demand. Furthermore, the distribution temperature in the space heating circuit can be lowered due to retrofitting [6]. This may significantly affect the design of the energy system, resulting in lower costs and CO_2 emissions. For instance, the reduction in the heat distribution temperature may lead to an increase in HP COP reducing operational costs. Secondly, the need for auxiliary high temperature technologies such as the natural gas boiler (GB) may be eliminated, resulting in savings in CO_2 emissions and investment costs. There are several levels of building envelope retrofits, such as window only retrofit, which includes multiple glazing, low emissivity coatings, air