Applied Energy 229 (2018) 1072–1094

Contents lists available at ScienceDirect

Applied Energy

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

Performance comparison between optimized design of a centralized and semi-decentralized community size solar district heating system

Hassam ur Rehman*, Janne Hirvonen, Kai Sirén

Aalto University, School of Engineering, Department of Mechanical Engineering, HVAC Group, PO Box PL 14400/Vi 351, 00760 Aalto, Finland

HIGHLIGHTS

- Centralized and semi-decentralized solar district heating systems are studied.
- Multi-objective optimization is carried out for both the systems and compared.
- High performance in decentralized system is realized at 35% lower lifecycle cost.
- The centralization of domestic hot water network increased the losses by 40–12%.
- Collector area vary to 5400 m^2 in centralized and 3000 m^2 in decentralized system.

ARTICLE INFO

Keywords:
Solar community
Seasonal storage
Centralized solar district
Decentralized solar district
Cold climate
Multi-objective optimization

ABSTRACT

Solar thermal energy is widely recognized as one of the most important renewable energy resources. However, in high latitudes, due to various climatic and mismatch challenges, such solar district heating networks are difficult to implement. The objective of the paper is to optimize and compare two different design layouts and control strategies for solar district heating systems in Finnish conditions. The two different designs proposed are a centralized and a semi-decentralized solar district heating system. The centralized system consists of two centralized short-term tanks operating at different temperature levels charged by a solar collector and heat pumps. Borehole thermal energy storage is also charged via these two centralized tanks. In contrast, the semi-decentralized system consists of one centralized low temperature tank charged by a solar collector and a borehole thermal energy storage and decentralized high temperature tank charged by an individual heat pump in each house. In this case, borehole thermal energy storage is charged only by the centralized warm tank. These systems are designed using the dynamic simulation software TRNSYS for Finnish conditions. Later on, multi-objective optimization is carried out with a genetic algorithm using the MOBO (Multi-objective building optimizer) optimization tool, where two objectives, i.e. purchased electricity and life cycle costs, are minimized. Various design variables are considered, which included both component sizes and control parameters as inputs to the optimization. The optimization results show that in terms of life cycle cost and purchased electricity, the decentralized system clearly outperforms the centralized system. With a similar energy performance, the reduction in life cycle cost is up to 35% for the decentralized system. Both systems can achieve close to 90% renewable energy fraction. These systems are also sensitive to the prices. Furthermore, the results show that the solar thermal collector area and seasonal storage volume can be reduced in a decentralized system to reduce the cost compared to a centralized system. The losses in the centralized system are 40–12% higher compared to the decentralized system. The results also show that in both systems, high performance is achieved when the borehole storage is wider with less depth, as it allows better direct utilization of seasonally stored heat. The system layout and controls varied the performance and life cycle cost; therefore it is essential to consider these when implementing such systems.

1. Introduction

Global energy consumption has been growing in the last few decades. Moreover, the combustion of fossil fuels for energy production has resulted in a huge environmental problems and emissions. Therefore, the increase in energy prices, the reduction in fossil fuel resources, and the impact on climate change have forced the masses to explore alternative and renewable sources in order to

* Corresponding author.
E-mail address: hassam.rehman@aalto.fi (H.u. Rehman).

https://doi.org/10.1016/j.apenergy.2018.08.064
Received 28 March 2018; Received in revised form 3 August 2018; Accepted 14 August 2018

Nomenclature

a_e	discounting factor
BTES	borehole thermal energy system
C_B	building investment cost (€/m^2)
C_{BTES}	borehole cost (€/m^3)
C_E	exported electricity price (c/kWh)
C_{Fins}	building floor insulation cost (€/m^3)
C_{HR}	building heat recovery cost (€)
C_{HT}	hot tank cost (€/m^3)
C_I	imported electricity price (c/kWh)
C_{PV}	photovoltaic panels cost (€/m^2)
C_{Rins}	building roof insulation cost (€/m^3)
C_{ST}	solar thermal collectors cost (€/m^2)
C_{WIND}	building windows cost (€/m^2)
C_{Wins}	building walls insulation cost (€/m^3)
C_{WT}	warm tank cost (€/m^3)
CO_2	carbon dioxide
COP	coefficient of performance
DHW	domestic hot water
DLSC	Drake Landing Solar Community
e_p	electricity price escalation rate
E_{BH}	direct electric backup heater electricity consumption (kWh/m^2/yr)
E_{BUL}	building appliances electricity consumption (kWh/m^2/yr)
E_{DEM}	total electricity demand of the system (kWh/m^2/yr)
E_{EXP}	exported electricity to the grid (kWh/m^2/yr)
E_{HP}	heat pump electricity consumption (kWh/m^2/yr)
E_{ONC}	on-site electricity demand, met by photo voltaic panel generation (kWh/m^2/yr)
E_{PUMP}	auxiliary pumps electricity consumption (kWh/m^2/yr)
E_{PUR}	purchased electricity from the grid (kWh/m^2/yr)
E_{PV}	electricity produced by the photovoltaic panels (kWh/m^2/yr)
ESTIF	European solar thermal industry federation
EU	European Union
HP	heat pump
HVAC	heating, ventilation, and air conditioning
i_r	interest rate
IEA	international energy agency
LCC	life cycle costs
LCOE	levelized cost of electricity
MOBO	multi-objective building optimizer
NSGA-II	Non-dominated Sorting Genetic Algorithm II
OEF_{elec}	onsite energy fraction for electricity
OSF	official statistics of Finland
PV	photo voltaic panels
REF_{heat}	renewable energy fraction for heating
SPH	space heating
ST	solar thermal collectors
TES	thermal energy storage

provide a sustainable future. On any sunny day, solar energy systems collect more energy than is needed for direct use [1]. Solar thermal is one of the most attractive renewable energy technologies and has huge market potential. It has been predicted that by 2020, the European Union (EU) will reach a total operational solar thermal capacity of around 320 GW [2]. However, the challenge is to develop efficient methods to collect, convert, store and utilize solar energy at affordable cost [3]. There are two main drawbacks in developing solar heating systems in Nordic region: (1) the resulting energy costs are not yet competitive and (2) solar energy is not available when needed. Research efforts are being made to develop methodologies that can help to overcome these challenges-developing low cost solar energy system architecture is one of those methodology [4].

The key to develop a low cost and high performing solar heating system is to build a large scale community sized solar heating networks, instead of a small or single building level heating system. Generally the main advantage of community sized district heating systems is their environmental benefits compared to a single building heating system [5]. It is found that a community-scale system and district heating are more beneficial than a single-house scale [6], as each building has a unique energy demand profile due to the different schedules in people's lives. This means that for a building cluster, a local energy generation or storage system can be sized to a lower capacity than for a single building [7]. A community has more controllable loads than a single building, therefore the matching is better. One option for a communal energy system is the centralized design where many buildings utilize a shared system. In a single-scale design, each building has its own generation and storage [8]. Joining single-building generation and energy storage units and controlling them centrally can improve the energy performance of the community [9]. Micro-girds are also proposed as an alternative to single building energy systems, where a micro grid can be built within the neighbourhood to share the energy [10]. A probabilistic portfolio-based model for financial valuation of community solar is proposed by Shakouri et al. and they found that community sized systems has shortest payback period [11]. The benefit of community is that the unit price is lower for large systems than for small systems [12], and large seasonal storage is feasible in large-scale applications [13].

In a community-sized solar energy system, heat storage can play an important role due to the mismatch between the demand and the generation. The cost advantage, due to the size and ability to operate at a seasonal scale allows ground thermal storage to be feasible technically and economically compared to short term storage [14]. Moreover, the integration of seasonal storage in district heating network has the potential to mitigate the CO_2 [15]. Among many types of ground storage, borehole thermal energy storage (BTES) is more attractive than other methods of seasonal storages. The main reasons are: its simplicity of design, its adaptability, its flexibility in term of the location and its cost effectiveness [16]. The issue with ground thermal storage is the heat loss [17]. The ground stores the heat in sensible form. To maximize the performance of the storage the heat loss needs to be minimized. The losses through the BTES depend on two main ground properties which are (1) thermal conductivity of the boundary layer and (2) groundwater level. Therefore, it is necessary to estimate the ground storage temperature to predict the losses and thermal conductivity of the ground. Beier et al. [18] provided an analytical model to estimate the vertical temperature profile of the ground storage. Numerical model is proposed to optimize the BTES operation by simulation, the objective is to minimize the losses through the BTES [19]. Spitler et al. [20] modelled techniques to reduce the losses in the BTES. They proposed that instead of low permeability grout, groundwater is filled in the annular space between the U-tube and the borehole wall. Welsch et al. [21] performed simulation to investigate the environmental and economic benefits of integrating borehole thermal energy storage in district heating network. It is found that with growing share of renewable energy mix, a combination of solar thermal, combined heat and power plant and borehole thermal energy storage can be economical with no subsidies. In the present study borehole thermal energy storage is used as seasonal storage. The average thermal ground conductivity of rocks in Finland is around 3.2–3.5 W/m K, the ground water is located at the depth of 1–4 m below the surface and, the bedrock in Finland is unbroken with little or no ground water flow [22].