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Thermo-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series

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ABSTRACT

Large-scale solar heating plants for district heating networks have gained great success in Europe, particularly in Denmark. A hybrid solar district heating plant with 5960 m^2 flat plate collectors and 4039 m^2 parabolic trough collectors in series was built in Taars, Denmark in 2015. The solar heating plant was used as a reference case in this study. A validated TRNSYS-GenOpt model was set up to optimize the key design parameters of the plant, including areas of both collector types, storage size, orientation of the parabolic trough collectors and so on. This study introduces a generic method to optimize the hybrid solar district heating systems based on levelized cost of heat. It is found that the lowest net levelized cost of heat of hybrid solar heating plants could reach about 0.36 DKK/kWh. The system levelized cost of heat can be reduced by 5–9% by use of solar collectors in the district heating network in this study. The results also show that parabolic trough collectors are economically feasible for district heating networks in Denmark. The generic and multivariable levelized cost of heat method can guide engineers and designers on the design, construction and control of large-scale solar heating plants.

1. Introduction

Solar energy is widely used in the building sector to supply space heating and cooling. Rad et al. [1] reviewed solar community heating and cooling systems with borehole thermal energy storage and gave suggestions about the development of borehole storage. Hazami et al. [2] simulated two domestic hot water systems with flat plate collectors and evacuated tube collectors separately and compared two systems by means of TRNSYS. Deng et al. [3] investigated a solar space heating system coupled with air source heat pump in TRNSYS. Kemal et al. [4] revealed the influence of the size of the storage tank on the performance and usability of solar water heating systems. Kaçan et al. [5] found that the actual optimum values for independent parameters have a vital importance for design engineer with respect to select the proper system component for solar heating system. Li et al. [6] discussed the operational strategy of a combined solar and ground source heat pump system for an office building in TRNSYS. Bellos et al. [7] did energetic and financial evaluation of solar assisted heat pump space heating systems with TRNSYS. Pardo García et al. [8] studied district heating configurations with photovoltaic thermal hybrid solar collectors for a central European multi-family house. Ramos et al. [9] also used TRNSYS to study a combined heating, cooling and power provision in the urban environment. Bava et al. [10] developed a numerical model to investigate the flow distribution in different operation conditions for solar district heating plants in Denmark. Bava et al. [11] also investigated pressure drop and flow distribution in a solar collector with horizontal U-connected pipes with this numerical model. Bava et al. [12] developed a detailed TRNSYS-Matlab model to simulate the thermal performance of large solar collector fields for district heating applications based on developed numerical model. Wang et al. [13] carried out energy, exergy and environmental analysis of a hybrid combined cooling, heating and power system utilizing biomass and solar energy. The vision of the Solar Heating and Cooling Programme of the International Energy Agency is “By 2050 a worldwide capacity of 5 kW_{th} per capita of solar thermal energy systems installed and significant reductions in energy consumption achieved by using passive solar and daylighting: thus solar thermal energy meeting 50% of low temperature heating and cooling demand (heat up to 250 °C)” [14]. Large-scale solar heating plants for district heating networks have developed fast in the last decades, and are one of the most successful applications of solar energy for the building sector.

1.1. Solar district heating plants

In the northern European countries, district heating networks have supplied both space heating and domestic hot water to many residents for many years. In the early 1980s, several large solar heating plants were installed in Sweden, which is the first country to apply large solar

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Nomenclature

Abbreviations

DH	district heating
DKK	Danish Krone
DRY	design reference year
DNI	monthly direct normal irradiance, kWh/m^2
E-W	east-west
FEP	fluorinated ethylene propylene
FPC	flat plate collector
HX	heat exchanger
IEA	International Energy Agency
LCOH	levelized cost of heat, DKK/kWh
LCOE	levelized cost of energy, DKK/kWh
nLCOH	net levelized cost of heat, DKK/kWh
N-S	north-south
PTC	parabolic trough collector
SHC	solar heating and cooling
sLCOH	system levelized cost of heat, DKK/kWh
TES	thermal energy storage

Latin symbols

A_{ptc}	aperture area of the parabolic trough collector field, m^2
A_{fpc}	aperture area of the flat plate collector field, m^2
C_{ptc}	cost of the parabolic trough collector field, DKK/m^2
C_{fpc}	cost of the flat plate collector field, DKK/m^2
c_1	heat loss coefficient at (Tm − Ta) = 0, W/(m^2·K)
c_2	temperature dependence of the heat loss coefficient, W/(m^2·K^2)
c_3	effective thermal capacity, J/(m^2·K)
C_t	operation and maintenance costs (year t), DKK
$C_{storage}$	specific costs of the tanks incl. installation (excl. VAT and subsidies), DKK/m^3
DEP_t	asset depreciation (year t), DKK
E_t	energy generated (year t), kWh
G	monthly global radiation, kWh/m^2
I_s	specific solar thermal system costs incl. installation (excl. VAT and subsidies), DKK/m^2
I_b	specific boiler system costs incl. installation (excl. VAT and subsidies), DKK
NE	heat from the natural gas boiler system, kWh
P_s	operation & maintenance expenditures of the solar plant in the year t, DKK
P_b	operation & maintenance expenditures of the natural gas boiler system in the year t, DKK
Q_{ptc}	yearly energy output of the parabolic trough collector field, kWh/m^2
Q_{fpc}	yearly energy output of the flat plate collector field, kWh/m^2
Q_{loss}	yearly heat loss in solar loop pipe and thermal energy storage, kWh
Q_O	yearly energy output of the whole collector field, kWh/m^2
r	discount rate, %
RV	residual value, DKK
SE	specific useful energy delivered by the solar thermal system in the year t (thermal losses in pipe loop and thermal storage considered), kWh
S_O	subsidies and incentives, DKK
T_a	ambient temperature, °C
I_O	initial investment, DKK
TR	corporate tax rate,%
T	period of use (solar thermal system life time in years), a
t	year within the period of use (1, 2, … T)

Greek symbol

η_O	optical efficiency, –

Subscript

th	thermal

collector arrays into district heating networks [15]. Recently, the number of large solar district heating plants has increased very fast in Denmark, Germany and Austria [16]. Fisch et al. [17] reviewed all the large-scale solar heating plants in Europe in 1998. IEA-SHC Task 7, 45 and 55 have focused on the application of large solar heating plants in district heating networks [14].

De Guadalfajara et al. [18] evaluated the potential of large solar heating systems with seasonal storage for 10 typical climate conditions in Spain. The system included a 2854 m^2 solar collector field. It was found that the estimated cost of the heat produced in large solar heating systems with seasonal storage with a solar fraction of 50% can be competitive with the heat cost of traditional domestic heat boilers in Spain. Bauer et al. [19] reviewed central solar heating plants with seasonal heat storage in Germany. Experiences from construction and operation of the research and pilot plants has led to technical improvement, higher efficiencies and cost reduction. Olsthoorn et al. [20] reviewed optimization methods on integration of renewable energy into district heating. The optimization method consists of a multi-objective method, sensitivity analysis, thermodynamic-economic analysis, and genetic algorithm. Tulus et al. [21] did multi-objective optimizations on central solar heating plants with seasonal storage in Spain. The results showed that central solar heating plants with seasonal storage led to significant environmental and economic improvements compared to the use of conventional natural gas heating systems. Life cycle assessment for economy and environment was carried out to optimize central solar heating plants. Guerreiro et al. [22] carried out the investigations on efficiency improvement and potential levelized cost of energy reduction with a linear Fresnel concentrator plant with storage. LCOEs showed that there was an enormous potential for the investigated plant. Sartor et al. [23] did simulations and optimizations of a CHP biomass plant and district heating network. The contribution presented a synthetic way to achieve such a task using only simple models on thermodynamic, combustion process, heat transfer and finance. The solar district heating system combined with borehole thermal energy storage (BTES) in Drake Landing Solar Community in Canada has managed to provide 96% of the community's annual space heating demand with solar heat for the period 2012–2016 [24].

Large solar district heating plants have gained great success in Denmark recently [25]. More than 1.3 million m^2 collectors are in operation in solar heating plants in Denmark by the end of 2016 [26]. Flat plate collectors have been used widely in the large-scale solar district heating plants in Denmark. Flat plate collectors have a bit lower efficiency at high temperature levels compared to evacuated tube collectors [27], Fresnel collectors and parabolic trough collectors [28]. Parabolic trough collectors are the more cost-effective at high temperature ranges such as 80–200 °C among these collectors [28]. Parabolic trough collectors are mainly used for solar power plants with oil or molten salt as heat transfer fluid. Parabolic trough collector with water as heat transfer fluid for direct steam generation also is an attractive option in electricity generation or industrial process [29]. Leiva-Illanes et al. [30] analyzed a solar poly-generation plant with parabolic trough collectors for electricity, water, cooling and heating in

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