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Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant

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ABSTRACT

Solar energy is an important alternative energy source that leads to sustainable development of district heating (DH) systems. The aim of this paper is to analyze optimal integration of photovoltaic thermal hybrid (PVT) technology in DH systems by covering industrial power consumption and heat demand of buildings in the Northern European climate.

The article compares several different scenarios for the particular case study in order to find the optimal solar system design. The scenarios differ with the size of the installed PVT area as well as an excess power utilization setup. The hourly load and solar energy generation alignment analysis determines the total achievable solar fraction and other parameters for each scenario.

The results show that it is economically beneficial to convert excess power to heat when the market price of electricity is lower than the DH heat tariff. This is done with the restriction that the heat demand is higher than solar heat generated. The higher solar fraction is obtained in scenario of maximal PVT area (3000 m^2) installation with a power accumulation added. Solar fraction reaches 38% of total heat and power consumption. However, this scenario also has the highest costs and incomes. The calculated value of levelized costs of energy (LCOE) for all scenarios is lower than used reference costs of energy.

The total avoided emissions are higher for the scenarios without power accumulation. The specific avoided CO_2 emission costs show that the optimal scenario is with 2000 m^2 PVT area installed.

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1. Introduction

As energy demand grows, its primary sources, like fossil fuel (natural gas, petroleum, coal, etc.), start to overcrowd consumption. The main activities what are close to energy use and fossil fuel consumption caused environmental pollution and rapidly changing weather conditions. In a long-term perspective, environmental pollution decreases when using renewable energy sources [1]. The renewable energy source integration in different sectors ensures the replacement of fossil fuel. In addition, European regulations set the goals, which the industrial sector should achieve in the next 10, 20 and 30 years [2]. Industry and building sector accounts for 49% of the overall final energy consumption and 36% of CO_2 emissions in the European Union (EU) [3,4].

Over time, district heating (DH) is developing continuously and stakeholders are looking for new solutions and technologies [5]. Therefore, new smart thermal grids begin to take an important role in sustainable development of DH systems [6,7]. Future DH systems have the potential to supply sustainable, trustworthy and intelligent energy to end users [8]. DH as a system is very flexible for the integration of renewable sources, but several scientists are devoted to the question how large will be the share of renewables in the short and long-term perspective [5,9,10].

The integration of solar energy in existing DH systems is a development opportunity [11–13]. It is expected that solar energy, especially solar energy based on photovoltaic (PV) technology, will make up a share of about 20% of total RES heat contribution by 2030 [4]. Solar energy integration in DH systems requires taking into account several aspects - necessity of thermal energy storage systems, importance of exergy analyses, essential government support and others. According to these main aspects, DH companies can decide to use solar energy for heat and power generation, as well as, power and heat can be transferred to grid, sold further, accumulated or used for self-consumption coverage [11]. Therefore, the authors further analyze the possibility to integrate hybrid photovoltaic thermal collector (PVT) in DH.

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Nomenclature

A	area, m^2
$B_{c,max}$	maximal charging level
$B_{c,min}$	minimal charging level
C_{Total}	total costs of PVT systemEUR
DH	district heating
E	escalation rate and
EF_{DH}	emission factor for power from grid, kg CO_2/MWh
EF_{power}	emission factor for power from grid, kg CO_2/MWh
GHI	global horizontal irradiation, hourly, kWh/m^2
$LCOE$	levelized costs of energy
$NOCT$	normal operating cell temperature, °C
NPV	Net Present Value, EUR
P_B	accumulated power, MWh
PBT	payback time
p_c	electricity consumption, hourly, kW
$p_{ex,i}$	excess solar power, hourly, kw
P_{gen}	generated solar power, MWh
P_{heat}	solar power converted to heat, annual, MWh
$P_{PVT,c}$	directly consumed solar power, annual, MWh
$p_{PVT,gen}$	generated power from PVT, hourly, kW
PR_{DH}	district heating heat tariff, EUR/MWh
PR_{el}	price of electricity from grid, EUR/MWh
PVT	photovoltaic thermal panel
$PR_{el,market}$	hourly market price of electricity, EUR/MWh
P_{sold}	sold solar power, annual, MWh
q_c	heat demand, hourly, kW
$Q_{PVT,c}$	directly consumed solar heat, annual, MWh
$Q_{PVT,conv}$	heat generated from excess solar power, annual, MWh
$q_{PVT,i}$	produced heat from PVT, hourly, kW
$Q_{PVT,T}$	total solar heat consumed, MWh
r	real interest rate
SF	solar fraction
STG	smart thermal grid
T_a	ambient outdoor temperature, °C
T_c	cell temperature (°C)
T_{water}	heat carrier temperature (°C)
$V_{heat,t}$	income from sold solar heat, EUR per Year
$V_{power,t}$	savings from grid electricity that was replaced by PVT energy, EUR per Year
$V_{sold,t}$	income from sold power, EUR per Year
α_1, α_2	heat loss coefficients, W/K/m^2
γ_{pf}	packing factor
γ_t	temperature coefficient (%/°C)
η_B	boiler efficiency
η_{cell}	PV cell efficiency
η_{PV}	PVT power generation efficiency
$\eta_{SC,i}$	PVT heat generation efficiency
τ_p	transmittance

PVT is a device that converts solar energy into electricity and heat. The process in PVT occurs simultaneously. Double PVT functions provide a higher overall solar conversion rate than just a photovoltaic (PV) or solar collector, thus allowing more efficient use of solar energy [14]. The high overall energy efficiency of a system means optimal use of roof space. On the contrary, PV panels and separately installed solar thermal collectors compete for roof space and at the same time set higher requirements for the same amount of heat and power produced by the PVT technology [3,15]. There are several benefits when using a PVT system: it is twofold (generate heat and power), effective and flexible (efficiency is higher than two separate systems), wide range of application (heat for heating and cooling, suitable also for domestic use) and practical (easily integrated) [4].

There are numerous studies analyzing the technological solutions and configurations of PVT panels. Lingkun et al. [16]. describe the novel solar PVT collector with dual channel using micro-encapsulated phase change slurry as cooling fluid which increases thermal and power efficiency. Modjinou et al. [17]. have developed a model of the PVT with a micro-channel heat pipe, but Hussain et al. [18]. proposes to improve the PVT with a honeycomb heat exchanger which leads to significant increase of thermal efficiency.

Several authors analyzed the use of PVT technology for building energy need coverage. Ramos et al. [19]. analyze the possibility to integrate the PVT in urban environment in order to ensure space and cooling needs. Authors developed the TRNSYS simulation model and the results show that the system can cover around 60% of the space and hot water consumption and almost 100% of the cooling demands of buildings. Therefore, the results show a lower levelised cost of energy than equivalent PV-only systems. Jahara et al. [20]. compare several PVT configurations and conclude that for domestic hot water applications, the hybrid flat heat pipe solar panels are suitable. Huide et al. [21]. compare application of different solar utilization technologies and conclude that PVT is favorable for the urban residential building with limited available installation space.

Pardo Garcia et al. [3]. investigate the possibility to combine PVT with DH to provide space heating and hot water in multi-family buildings. Authors conclude that such configuration can increase the system sustainability, energy security, carbon abatement and reduce costs. However, the most favorable results are reached when the heat can be fed into the DH network.

However, at this time there is no scientific research on larger scale PVT system installation in colder climate zones for integration in DH system. The aim of this paper is to analyze optimal integration of PVT technology for the Northern European climate, by covering industrial power consumption and heat demand of buildings. The hourly analyses have been made in order to determine potential solar fraction.

2. Methodology

2.1. Case study and scenarios

The case study of the research is a boiler house of a DH system, which supplies the heat for space heating and domestic hot water preparation. The boiler house uses natural gas as an energy source for heat production and is directly linked to the industrial consumer with particular heat and electricity consumption. The DH Company considers using solar energy instead of natural gas to reduce energy prices and overall environmental impacts. Research analyzes the installation of PVT technology and integration into the existing DH system because there are both heat and power consumers. Fig. 1 shows the system boundaries and energy flow connections.

Authors compare several different scenarios in order to find the optimal design of the solar system for the particular case study. The scenarios differ in terms of the size of installed PVT area and an excess power utilization setup (see Table 1) (further described in Section 2.3.).

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