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Smart thermal grid with integration of distributed and centralized solar energy systems

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ABSTRACT

Smart thermal grids (STGs) are able to perform the same function as classical grids, but are developed in order to make better use of distributed, possibly intermittent, thermal energy resources and to provide the required energy when needed through efficient resources utilization and intelligent management. District heating (DH) plays a significant role in the implementation of future smart energy systems. To fulfil its role, DH technologies must be further developed to integrate renewable resources, create low-temperature networks, and consequently to make existing or new DH networks ready for integration into future STGs. Solar heating is a promising option for low-temperature DH systems. Thermal energy storage (TES) can make the availability of the energy supply match the demand. An integration of centralized seasonal and distributed short-term thermal storages would facilitate an efficient recovery of the solar energy. This study, through modelling and simulation, investigates the impacts of such integration on the overall performance of a community-level solar DH system. The performance analysis results show that the solar DH system with integration of distributed and centralized seasonal TESs improves system overall efficiency, and reduces DH network heat losses, primary energy consumption and greenhouse gas emissions, in comparison to the one without integration.

1. Introduction

The advancement from a smart electric grid to the Smart Energy Networks (SENs) concept has extended the boundary of the smart grid to include all three main energy vectors: electricity, thermal and gas, into one network under a common Information and Communication Technology (ICT) for better management, efficient utilization and increased participation of distributed generation and renewables, and for achieving climate mitigation and energy supply security targets [1–4]. Smart thermal grid (STG) will be an integral element in the future SENs by ensuring a reliable and affordable heating and cooling supply.

Connolly et al. [5] and Lund et al. [6] define the concept of smart thermal grids as a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and/or cooling production units including individual contributions from the connected buildings. Classical thermal grids, or district heating and cooling networks, have a clear distinction between the heating/cooling producer and the heating/cooling consumer, whereas smart thermal grids enable feed-in from consumers (or so called prosumers). These customers then become temporary producers, adding energy to the grid rather than drawing from it. The two-way energy exchange between consumer and the grid, and the ability to manage this intelligently and efficiently distinguishes smart grids from classical grids. Therefore, smart thermal grids will be able to make better use of distributed heat from various renewable energy resources (e.g. solar and geothermal) and industrial surplus heat sources. Schmidt [7,8] summarizes that a smart thermal grid should have the following capabilities: innovative planning and financing schemes, intelligent network operation, customer interaction, cascade usage of resources and integration into the urban energy systems.

According to International Energy Agency report [9], heating

Abbreviation: AH, Air handler; BTES, Borehole thermal energy storage; CCHT, Canadian Centre for Housing Technology; CWES, Canadian weather for energy calculations; DH, District heating; DHW, Domestic hot water; DLSC, Drake Landing Solar Community; EF, Emission factor; GHG, Greenhouse gas; GT, Gas tank; HEX, Heat exchanger; ICT, Information and Communication Technology; PEF, Primary energy factor; SEN, Smart energy network; SF, Solar fraction; SPT, Solar preheat tank; STG, Smart thermal grid; STTES, Short term thermal energy storage; TES, Thermal energy storage.

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Nomenclature

G	Solar radiation, W/m^2
$K_{\alpha T}$	Incidence angle modifier
Q_{load}	Thermal load (space heating and DHW loads), GJ
Q_{loss}	Heat losses from a system, GJ
Q_{solar}	Solar energy supplied to a system, GJ
T_a	Ambient temperature, °C
T_i	Solar collector fluid inlet temperature, °C
η_c	Solar collector thermal efficiency
θ	Incident angle for beam radiation, °

and cooling accounted for approximately 46% of the total global energy use in 2012 and district heating (DH) accounts for a major part of this energy consumption [10]. While market penetration of district heating reaches as high as 70% of the heating market in some countries, district cooling has emerged quite recently and is consequently less developed than the district heating market [8].

A number of recent studies [6,11–18] have investigated the role of district heating in the future smart energy systems based on high penetration of renewable energy as well as substantial reductions in building heating demand. These studies come to the conclusion that district heating plays a significant role in the implementation of future smart energy systems. However, in order to be able to fulfil its role, district heating technologies must be further developed to decrease grid losses, exploit synergies, and thereby increase the efficiencies of low-temperature production units in the system [6] and consequently make existing or new district heating networks ready for integration into future smart thermal grids and smart energy networks.

Solar heating is a promising option for low temperature DH systems and future STGs, but a drawback of solar heating is the mismatch between summer supply and winter demand. Consequently, if solar heat is to supply a significant portion of building heat, thermal energy storage (TES) is a requirement. TES is a bridge to close the gap between the energy demand of a DH system and the energy supply to the DH system [19,20] and is often used for exploiting renewable energy sources [10,21,22]. Small short-term storage systems can be located inside buildings, but in order to achieve high solar fractions in an economic way, large seasonal storage systems are required. Long term seasonal storage allows thermal energy storage over weeks and months and is particularly important for solar communities where energy availability is much higher in the summer, in contrast to the much higher demand during winters.

Since 1970, the seasonal thermal storage technology, as part of a district heating system, has been under exploration and inspection [23]. Most past and present systems have stored heat in sensible form, since cost is an issue and these systems use mostly water, rocks and soil as storage medium [20]. There are four types of sensible seasonal energy storage in operation: hot water thermal energy storage, gravel-water thermal energy storage, borehole thermal energy storage and aquifer thermal energy storage [23–25]. The selection of a specific store type depends on the geological and hydrogeological situation in the ground at the respective construction site [25]. Based on comprehensive literature review, Rad et al. [23] concluded that borehole thermal energy storage (BTES) has the most favorable condition for long-term energy storage, because the large amounts of energy involvement and relatively low cost of storage media.

Rad et al. [23] and Gao et al. [26] have presented the technical characteristics of some large-scale demonstration plants with thermal collectors and BTES located in Germany (Neckarsulm, Attenkirchen, Crailsheim), Sweden (Anneberg) and Canada (Drake Landing Solar Community). For the mentioned demonstration plants in Germany, the space heating and domestic hot water (DHW) preparation are supplied by the centralized solar plant backed-up by heat pumps (Neckarsulm plant also with backup gas boilers). Anneberg plant in Sweden uses individual electric heaters for providing supplement heat in times when the centrally-stored solar energy is not sufficient to meet the space heating and DHW demands. On the other hand, the centralized solar plant in Drake Landing Solar Community (DLSC) is for supply space heating only, and a separate solar energy system installed for each house is used for DHW preparation. This study is interested in investing the solar BTES system alike the DLSC one and to explore the potential of integration of the centralized and distributed solar thermal energy storage systems.

The Drake Landing Solar Community in Canada is a planned neighbourhood with 52 R–2000 single family homes, in the town of Okotoks, Alberta, equipped with a central solar district heating system with short- and long-term (seasonal) thermal energy storages. Systems of similar size and configuration have been constructed in Europe, however, this is the first system of this type designed to supply more than 90% of the space heating with solar energy and the first operating in such a cold climate (5200° C-days) [27]. In 2012 (after 5 years in operation), the system achieved a world record solar fraction of 97%, and a reduction of approximately 5 tonnes of greenhouse gas (GHG) emissions has been attained per home per year compared to those with conventional heating systems [28]. To meet domestic hot water (DHW) demands, every home in the Drake Landing Solar Community is equipped with two unique, self-regulated solar panels on the roof of the house. These solar panels are connected to a solar hot water tank in the basement. On an annual basis, approximately 60% of the home's domestic hot water requirements are met using solar energy [29]. When solar energy is not available, the hot water demands are supplemented by a back-up natural gas, power-vented hot water tank unit.

Typically domestic hot water demand peaks in the morning and evening, and there is little or even no usage (e.g. for working family with school-age children) during the day. In this case the solar energy available/sufficient in the daytime will not be fully collected due to the limitation of the solar hot water storage tank capacity/volume. One way to further improve the efficiency of the local distributed solar systems is to integrate them to the centralized DH system for space heating at times there is no or low DHW demand. The energy from the centralized DH centre will be drawn to top-up the space heating demand when it is required. In this way, the capacity of the distributed solar systems will be fully utilized, and in addition, the frequency of calling energy transfer from centralized short term energy storage and BTES to each home will be lowered. It is expected that the pumping power to move the energy from and back to the centralized solar energy plant as well as the network heat losses will be reduced.

This study is to investigate the impacts of integration of local distributed solar storage system with centralized long-term storage system on the overall performance of a community-level solar district heating system; and to develop modelling tools that can be used for the optimization of solar thermal storage applications ready for inclusion in the future smart thermal grids and smart energy networks.

2. Solar district heating systems for case studies

An alternative solar district heating system, with the interaction of the local solar energy system to the centralized solar district