Energy and Buildings 152 (2017) 359–372

Contents lists available at ScienceDirect

Energy and Buildings

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

Comparison of solar thermal systems with storage: From building to neighbourhood scale

Shanshan Hsieh[a,b], Akomeno Omu[a,b], Kristina Orehounig[a,b,*]

[a] Chair of Building Physics, Swiss Federal Institute of Technology, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland
[b] Urban Energy Systems Laboratory, EMPA, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland

ARTICLE INFO

Article history:
Received 12 November 2016
Received in revised form 8 June 2017
Accepted 12 July 2017
Available online 17 July 2017

Keywords:
Solar thermal energy system
Thermal energy storage
Energy system modelling

ABSTRACT

The temporal fluctuation of solar energy resources often require the utilization of thermal energy storage to increase the level of solar energy. Solar energy systems that are used to meet the heating demands of buildings can be implemented in a variety of system configurations, ranging from energy production and storage at the building-level, to centrally located production and storage components coupled with a district-heating network. In this paper, quasi-steady state simulation models are used to evaluate the impact that different design configurations of decentralized and centralized solar thermal systems (with short- and long-term storage) have on the overall economic cost of the energy provision and the degree of solar energy utilization. A suburban neighbourhood in Switzerland consisting of 11 buildings is selected as a case study. Simulation results suggest that building-level long-term storage configurations out perform all other system configurations in terms of solar fraction and system efficiencies for the given case study. Furthermore, the results demonstrate that the location of the thermal storage and the separation of short- and long-term storage are crucial issues that affect the performance of building-level renewable energy sources, and thus merit further investigation.

1. Introduction

Thermal energy demand accounts for more than 50% of the total building energy demand in Switzerland [1] and EU27 countries [57]. Therefore, as countries look to decrease their per capita CO_2 emissions, the need for renewable heating sources for the building sector is becoming an increasingly important topic. Although solar thermal systems are a well-established building-level technology for the provision of domestic hot water (DHW), as space heating (SH) demands have decreased due to higher standards of building envelopes and systems, solar combi systems, which are able to supply both DHW and SH, are becoming more popular in some European countries (e.g. Austria, Denmark, Germany and Switzerland) [2]. Since it can level out the temporal mismatch of supply and demand, the integration of thermal storage technologies is essential to increasing the fraction of energy demand that is supplied by solar energy. Thereby, short-term storage can overcome the mismatch of hourly, diurnal or weekly differences, while long-term storage can overcome seasonal variations [3].

In addition to systems at the scale of single buildings, large scale solar thermal energy systems combined with district heating networks are increasingly being regarded as an efficient and cost effective technology option, due to the possibility of using large storage volumes of long-term storage at a centralized location, and thus improving the utilization of installed solar collectors [4]. Currently, the integration of solar thermal collectors is mainly assessed at the building level [5,6]. However, in cities, where available roof surface is scarce, large centralized ground or industrial areas provide an additional potential of accumulating solar thermal-based energy, which can then be delivered to the buildings through thermal networks.

Several system configurations exist to utilize solar thermal resources in neighborhoods, ranging from centrally produced and stored solar thermal systems supplying heating demands in a neighbourhood [7], to decentralized building integrated production and storage schemes [8]. Combinations of building integrated production and centralized storage for single family houses [9] have also been designed already. The design of such systems is complex, and while the advantages and disadvantages of building integrated solutions in comparison to centralized solutions

* Corresponding author at: Chair of Building Physics, Swiss Federal Institute of Technology, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland.
E-mail address: orehounig@arch.ethz.ch (K. Orehounig).

http://dx.doi.org/10.1016/j.enbuild.2017.07.036

Nomenclature

Configurations

*D_*	Decentralized produced energy from solar collectors
*C_*	Centralized produced energy from solar collectors
N	No storage
DS	Decentralized short-term storage
DL	Decentralized long-term storage
DSL	Decentralized storage combined with short- and long-term storage volumes
CL	Centralized long-term storage

Symbol

A	Surface area [m^2]
q	Heat transfer rate [W]
Isolar	Solar irradiance [W/m2]
F_R	Correction factor of solar collectors [-]
τa	Effective transmittance-absorptance of solar collectors [-]
U_L	Overall heat loss coefficient [W/(m^2K)]
T	Temperature of the working fluid entering solar collectors [K]
T_a	Ambient temperature [K]
c_p	Specific heat of fluid [J/(kgK)]
M	Mass of fluid [kg]
h	Surface heat transfer coefficient [W/(m^2K)]
CHP	Combined heat and power generation
DH	District heating
DHW	Domestic hot water
HX	Heat exchanger
LC	Levelized costs
SE	System efficiency
SF	Solar fraction
SFH	Single family house
SH	Space heating demand
V_{tank}	Storage tank volume

Subscripts

a	Ambient air
n	Numbers of vertically divided nodes in the storage tank
s	Storage tank
c	Solar collectors
p	Piping of the district heating network
f	Heat transfer fluid within the district heating pipe
i	Axially divided district heating pipe section
wall	District heating pipe wall
e	Exterior surface surrounding the district heating pipe

are often discussed, there has been little research into analyzing the various system configurations for the same demand case in order to quantitatively draw conclusions about the impact that a system configuration has on the system's performance. Since the utilization of solar systems would substantially benefit from increased knowledge in system design [10], more configurations including the spatial distribution of solar collectors and storages should be studied. System configuration studies which were performed include Pietra et al. [11] who compared buildings with solar thermal systems and storages integrated in the same district. One stand-alone configuration is analysed along with another configuration that consists of building-level solar thermal collectors connected to a district heating network with a centralized combined heat and power (CHP) plant. Results show that the percentage of the annual solar thermal energy production that could be used to meet the annual energy demand increased from 28% to 108%, showing the potential benefit of enabling the entire district to utilize excess solar thermal energy from building level collectors. However, the storages are all kept at the building level in their study. Yang et al. [14] compare two solar district heating configurations which are equipped with centralized production and storage. Differences of these two configurations lie in whether the building level solar collectors supply both SH and DHW or not. Results show that distributed solar collectors which supply both SH and DHW outperform the other system. Moreover, Bachmaier et al. [12] showcase the need for different spatial distributions of thermal energy storage at various locations with differing demand characteristics and storage space availability. They evaluated different scenarios for a district with a CHP supplying heat through a district-heating network for different sizes of centralized and decentralized thermal storages. Optimization results, which include the sizing of the CHP plant, thermal storage capacities and installed locations, showed that decentralized storage configurations function as efficiently as centralized storage configurations with optimal sizing and operation. While the aforementioned studies show the potential for increasing the system performance of solar thermal energy systems through the consideration of system configurations, a thorough assessment of different configurations, with varying solar thermal production and storage placements, and the integration of components, has not been performed so far in the literature.

The behavior of thermal storage systems is complex; therefore, detailed modelling is required in order to rigorously compare the performance of the different configurations. Solar thermal system modelling can be done in different ways depending on the purpose of the analysis. Steady state modelling approaches are typically used for sizing the system, taking peak heating demands into account. However, an accurate representation of the system performance is strongly dependent on the varying temperature states over a period of time. For example, the behavior of a district-heating network heavily influences its performance due to the time delay caused by the distance between the heat source and the consumer, and the network heat capacity [13]. Varying temperature levels within the storage volumes, as well as charging and discharging cycles are also critical parameters that can be more accurately assessed through dynamic system modelling approaches.

In the field of solar thermal energy system analysis, dynamic modelling tools, including TRNSYS [63], Modelica [64], and EnergyPlus [20], have been used in various studies. Terziotti et al. [5] used TRNSYS to model solar collectors together with a seasonal solar thermal energy storage system at building level. Yang et al. [14] used the same modelling tool to compare two storage system configurations with solar district heating. Soons et al. [15] and Batista et al. [16] explored the capacity of Modelica to model district heating networks with multiple energy production units, thermal storage, as well as heat and cold consumers. Batista et al. [16] showed that Modelica is a powerful tool to model thermal energy storage in DH networks, and when it is combined with simplified building models, that it is able to perform accurate simulations in reasonable time. The tool EnergyPlus which is used in this study has been widely used for building energy consumption modelling. The software provides various validated supply system models, which can be used to study the energy performance of buildings together with building system operation. For instance, Li et al. [66] studied various operation strategies of a neighbourhood energy system, and EnergyPlus was used to model a thermal storage shared among two buildings. In this study, the simulation model is coupled to another software which accounts for the control strategy. Raffenel et al. [67] demonstrated a procedure for solar combi-system sizing of a building. They used EnergyPlus to model the solar combi-system with