Energy 152 (2018) 533–538

Contents lists available at ScienceDirect

Energy

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

Simulation method for a pit seasonal thermal energy storage system with a heat pump in a district heating system

Peter Sorknæs

The Technical Faculty of IT and Design, Department of Planning, Aalborg University, Aalborg, Denmark

ARTICLE INFO

Article history:
Available online 29 March 2018

Keywords:
Seasonal thermal energy storage system
District heating
Heat pump
Simulation
Solar thermal
Dronninglund district heating

ABSTRACT

To better facilitate renewable energy systems, the district heating sector is currently changing towards lower temperatures and increased cross-sectoral integration. Seasonal thermal energy storage systems alongside heat pumps have received an increasing attention. However, the operation of a seasonal thermal energy storage system alongside a heat pump is more complex than a short-term thermal energy storage system, and as such, several complex simulation models have been developed. These models have shown to be usable for simulating the operation, but due to their complexity are difficult to implement in simulation models that focus on overall energy system analyses. Based on the operation of an existing seasonal thermal energy storage system, this paper provides a simulation method for a seasonal thermal energy storage system with a heat pump that can be utilized in overall energy system simulation models. The simulation method is based on the proven different operational situations of the seasonal thermal energy storage system. The method is shown to be able to approximate the actual operation on an hourly basis and the yearly thermal losses.

1. Introduction

Many countries' energy systems are gradually being changed with increasing amounts of renewable energy sources (RES) in the different energy sectors alongside increasing energy efficiency. Within the district heating sector this has brought the focus on both lower temperatures and increased energy system integration using e.g. heat pumps and CHP, as was also argued by Lund et al. [1], in regards to the so called 4th generation district heating (4GDH). Lund et al. [1] argues that 4GDH increases the potential for utilising otherwise wasted sources of thermal energy, e.g. industrial excess heat and increases the efficiency of the energy producing units.

As part of integrating more RES into the low temperature district heating systems, seasonal thermal energy storage systems (STESS) have seen an increasing implementation, as these have shown to allow for a greater integration of solar thermal heating in district heating systems [2]. Especially sensible thermal energy storage systems have seen increased implementation in district heating systems utilising solar thermal energy, whereas latent and chemical thermal energy storage systems are still in the laboratory study stages of development [3]. Dronninglund District Heating in Denmark is an example of a district heating plant that has used a STESS to increase the utilisation of solar thermal energy in the district heating system. Here a 60,000 m^3 pit STESS has in 2014 been implemented alongside about 37,600 m^2 of solar collectors and an absorption heat pump [4]. In 2015 this resulted in a solar fraction of 41% [5]. District heating systems without STESS cannot normally exceed a solar fraction of about 20% [2]. The operational temperature at different depths of the pit STESS at Dronninglund District Heating since it went into operation, can be seen in Fig. 1.

The maximum energy storing capacity (Q_{max}) in [J] of a thermal energy storage system is often found using Equation (1).

$$Q_{max} = V^*u^*\rho^*c_p^*(T_{top} - T_b) \quad (1)$$

where V is the volume of the storage [m^3], u is the % of the volume that can be utilised, ρ is the density of the water [kg/m^3], c_p is the specific heat capacity of the water [J/(kg*K)], T_{top} and T_b is the temperature in the top and bottom [K], respectively.

In a district heating system T_{top} will normally be equal to or higher than the forward temperature in the district heating system ($T_{f\text{-}DH}$), to utilise the energy directly. T_b will normally approximate the return temperature of the district heating system. However, as can also be seen in Fig. 1, a pit STESS with a heat pump makes that approach problematic. The reason being that the utilisation of a

E-mail address: sorknaes@plan.aau.dk.

https://doi.org/10.1016/j.energy.2018.03.152
0360-5442/

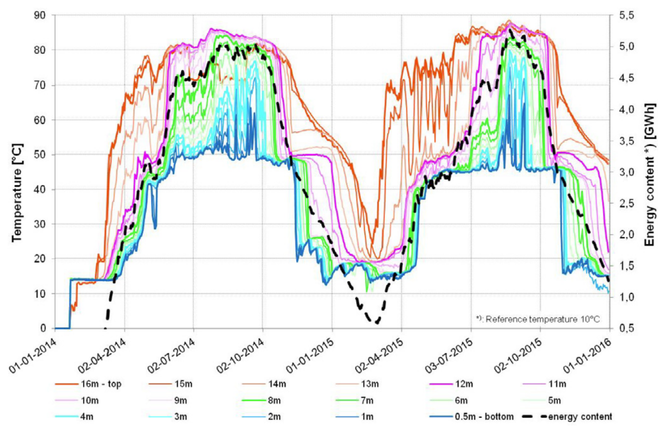

Fig. 1. Temperature and energy content development in the pit STESS at Dronninglund District Heating from start of operation to 1st of January 2016 [5].

heat pump provides a new option, where T_{top} could be lower than $T_{f\text{-}DH}$, and T_b can in periods of heat pump utilisation equal the output temperature of the cold side of the heat pump ($T_{b\text{-}hp}$). For this reason, a STESS utilising a heat pump requires a different method.

As such, simulation methods for pit STESS has received focus within research. Hesaraki, Halilovic and Holmberg [6] studied the application of a stratified STESS with a heat pump as backup at individual building level. The STESS was divided into 10 layers with different temperatures. The model was developed in MATLAB. Guadalfajara, Lozano and Serra [7] presents a simple method for calculating the size of a central solar heating plants with STESS to be used in the early stages of a project. The simple method is without stratification in the STESS, which is expected to underestimate the performance of the system, though it is noted that a study done by Braun et al. [8] found that stratification effects only have a negligible effect on the yearly performance of a STESS. Guadalfajara, Lozano and Serra's simple method is validated on a case simulated in the transient simulation program TRNSYS. It is found that the presented simple method showed a heat loss from the STESS that was like that found in the TRNSYS simulation. However, this simple method does not include a heat pump for when the temperature is too low in the STESS. Marx, Bauer and Drueck [9] investigates solar district heating with a STESS in connection with a heat pump that uses the STESS as a low temperature heat source. The STESS analysed is an underground hot water tank. The study finds that using a heat pump has a positive influence on the performance of the other components in the system, though the study finds it questionable whether the use of an electric-driven heat pump is feasible from an economic and CO_2-emission perspective. The study is based on simulations in TRNSYS. Lund [10] presents a simulation model for a specific setup with an uninsulated hot water tank excavated in stable bedrock and vertical heat exchangers alongside its sides. The model includes a heat pump, solar collectors, and a short-term thermal energy storage in a district heating system. The model details the temperatures of the energy flows between the different units in the district heating system on an hourly basis in the software NORSOL. Lund [11] develops an analytical methodology to analyse the effects of varying degrees of stratification on the performance of a STESS and connected solar collectors in a simple analytic form. The use of a heat pump is not included in the methodology, though it is stated that the methodology is applicable with heat pump systems. Reuss, Beck and Müller [12] investigates the heat transfer coefficient and heat capacity of soil depending on water content, mineral composition, dry bulk density and shape of soil components of a borehole STESS. The paper also tests on a specific test case of a small district heating system with solar thermal and CHP using an hourly computer simulation done in TRNSYS-DST. Claesson and Eskilson [13] develops a tool for analysing a borehole STESS to be used as a heat sink for a heat pump. The tool includes detailed approaches e.g. for simulating the effect of heat extraction rates on the extraction temperature.

From the research it is found, that complex simulations models, such as TRNSYS, are often used for simulating STESS with a heat pump. Though, the research has mainly focused on providing very precise, and thereby complex, simulation models. These complex simulation models have shown useful for simulation of case STESS, though they are generally too complex for many energy-only models used both in research and in the industry, such as EnergyPLAN [14] and energyPRO [15], where the temperature levels of the energy flows are not detailed between the different energy units and STESS are often modelled using Equation (1) or a similar simple approach. Also, some simulation models are so simple that they cannot account for the added complexity that a heat pump adds to the operation of a STESS. Having a simulation model for a STESS that includes a heat pump's added complexity is especially relevant due to the increasing importance of heat pumps, especially electric-driven, in energy systems based on RES [16].

The purpose of this paper is to provide a simulation model for a pit STESS with a heat pump in a district heating system that is both complex enough to include the different operational situations of the storage and the variation in the heat pump COP, while keeping it simple enough to be useable in more simple energy-only simulation models, that are used for e.g. energy system analyses or in the predesign process, where only energy amounts to and from the pit STESS are needed. As such, here the simplicity is understood as the model will only get the input in thermal energy amounts and the output will only be in thermal energy amounts, where the STESS and the accompanying heat pump are for modelling purposes seen as one single unit. The simulation approach is set up to be useable for simulation of one or more years on time steps of e.g. hourly level.

2. Methodology

2.1. Physical attributes

A pit STESS is normally built in the form of an obelisk turned upside down [17], and hence the volume and the surface area can be calculated based on this physical form.

Based on Fig. 2, the volume (V) [m^3] of a pit STESS is found as shown in Equation (2). h, a, a_1, b and b_1 are in [m].

$$V = \frac{h}{6}((2a + a_1)b + (2a_1 + a)b_1 \quad (2)$$

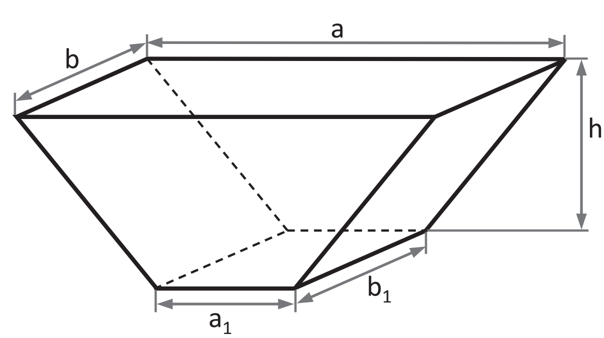

Fig. 2. Illustration of the shape of a pit STESS.