A modular approach to inverse modelling of a district heating facility with seasonal thermal energy storage

Tordrup, Karl Woldum; Poulsen, Uffe Vestergaard; Nielsen, Carsten

Published in: Energy Procedia

DOI: 10.1016/j.egypro.2017.09.518

Publication date: 2017

Document Version
Publisher's PDF, also known as Version of record with the publisher's layout.

Link to publication

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Download policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 24. jan., 2020
A modular approach to inverse modelling of a district heating facility with seasonal thermal energy storage

Karl Woldum Tordrup, Uffe Vestergaard Poulsen, Carsten Nielsen
Centre of Applied Research and Development in Building, Energy & Environment, VIA University College, 8700 Horsens, Denmark

Abstract

We use a modular approach to develop a TRNSYS model for a district heating facility by applying inverse modelling to one year of operational data for individual components. We assemble the components into a single TRNSYS model for the full system using the accumulation tanks as a central hub connecting all other components. We compare predictions of the total heat delivered to the district heating network to observed values and find a model error of 7.1% for one simulation year.

© 2017 The Authors. Published by Elsevier Ltd.
Peer-review under the responsibility of EUROSOLAR - The European Association for Renewable Energy.

Keywords: District heating; borehole thermal energy storage; inverse modelling.

1. Introduction

District heating systems potentially offer an economically attractive means of reducing carbon dioxide emissions by offering a more effective use of renewable resources as well as recycling of heat production which would otherwise be wasted [1]. In systems with high solar fractions, seasonal thermal energy storage is a key component in order to balance supply and demand, usually in the form of either hot water heat storage [2] or borehole thermal energy storage (BTES) [3,4].

Heat production in Denmark is to be based exclusively on renewable energy sources by 2035. Since 64% of Danish households are supplied by district heating, and the district heating network currently incorporates 86 facilities with solar collector arrays [5], there is an increasing demand for thermal energy storage. A similar development towards higher renewable fractions is underway for electricity production. The target for Denmark is to be completely independent of fossil fuels by 2050, which calls for a tighter integration of thermal and electric power systems. An important tool in supporting this transition is the development of reliable numerical models of large scale solar seasonal storage systems to aid in scenario analysis and control strategy development [6,7].

* Corresponding author.
E-mail address: kart@via.dk
In the present work we focus on the district heat facility in Brædstrup, Denmark, and develop and validate a TRNSYS model of the facility by applying inverse modelling to operational data at the component level. This approach serves to limit the search space for the numerical optimisation and can in principle be applied to a system of any size. The calibrated system components are used to construct a model of the entire system and predictions from this full model are finally compared to observed data.

The paper is organised as follows. In Section 2 we give a brief description of the district heating plant. In Section 3 we describe a modular approach to inverse modelling of a large system and describe how the final model is constructed from the components. In Section 4 we present and discuss results. Section 5 concludes the paper.

2. System description

The district heating facility in Brædstrup delivers heat and power to approximately 1450 households. A schematic overview of the plant is given in Fig. 1.

![Simplified diagram of the district heating facility.](image)

The plant has two natural gas engines with a combined electrical power of 7.28 MW and thermal power of 8.0 MW. Additionally the plant has a 13.5 MW natural gas boiler, a 10 MW electrical boiler and two steel accumulation tanks with volumes 2000 m³ and 5000 m³ respectively. Renewable heat production is provided by two solar collector fields with individual total areas of 8000 m² and 10,600 m² respectively. Excess heat produced by the collector fields during summer is stored in a 19,000 m³ borehole thermal energy storage (BTES) and retrieved using a 1.2 MW heat pump during winter.

3. Methods

We develop a TRNSYS model for the entire facility by applying inverse modelling at a component level. For each component, a separate TRNSYS model is constructed which reads the relevant input data such as inlet temperature and flow rate from an external data file. A forward simulation is run for 365 days and simulated outlet temperatures are recorded. These outputs depend on one or more component parameters e.g. the efficiency and are compared to the operational measurements. For each component a meaningful objective function is constructed to quantify the discrepancy between the observed and simulated outputs. Finally we calculate the best component parameters by...
minimising the objective function, i.e. we calculate the component parameters that give model predictions that most closely resemble the observed outputs.

Operational data was extracted from the plant’s SCADA system at a resolution of 5 minutes for 365 days starting on January 1st 2014. These data serve as the calibration data set for all components as described in the following sections. For all components apart from the heat pump, the calibration was performed using the Hookes-Jeeves method implemented in TRNOPT.

3.1. Solar collector fields

The district heating facility has an 8000 m² collector field opened in 2007 as well as a newer 10,600 m² field opened in 2012. The two collector arrays may not display the same characteristics, so a separate model is developed for each field. For both fields the collectors are modelled as flat plate collectors with quadratic efficiency (TRNSYS type 1b), i.e. the efficiency is assumed to be of the form

\[ \eta = a_0 - a_1 \frac{\Delta T}{I_T} - a_2 \frac{\Delta T^2}{I_T}, \]  

where \( \Delta T = T_{\text{av}} - T_{\text{amb}} \) is the average collector temperature minus the ambient temperature, \( I_T \) the incident solar radiation and \( a_0, a_1 \) and \( a_2 \) are efficiency parameters specific to the collectors. The collector fluid specific heat is 3.973 kJ/kg/K for both fields and the collector slope is 40°. The measured operational data are the inlet temperature, the outlet temperature, the flow rate through the collectors, the ambient temperature and the incident radiation.

In order to assign higher weights to observations with higher energy we choose the objective function

\[ \varphi_{\text{coll}} = \sum \dot{m}(T_{\text{out}}^{(s)} - T_{\text{out}}^{(m)})^2, \]  

where \( T_{\text{out}}^{(s)} \) and \( T_{\text{out}}^{(m)} \) are the simulated and measured outlet temperatures respectively and the summation is over all time steps in the simulation. Minimizing the objective function separately for the two collector fields we obtain the efficiency parameters shown in Table 1. Note that in both cases the second order coefficients were terminated at the lower bound \( a_2 = 0 \) during the optimisation.

<table>
<thead>
<tr>
<th></th>
<th>Old field</th>
<th>New field</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 [-] )</td>
<td>0.7575</td>
<td>0.7800</td>
</tr>
<tr>
<td>( a_1 [W/m^2/K] )</td>
<td>4.5087</td>
<td>4.3359</td>
</tr>
<tr>
<td>( a_2 [W/m^2/K^2] )</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The average absolute temperature discrepancy for the old and new fields during times with non-zero flow are 8.2 °C and 3.7 °C respectively. A comparison of simulated and observed accumulated energy delivered from the collector fields is shown in Fig. 2.

3.2. Heat exchangers

The two solar collector fields in the system have separate heat exchangers between the water and glycol sides. We model these as constant effectiveness heat exchangers (type 91). We set the load side specific heat to 4.19 kJ/kg/K and the source side to 3.973 kJ/kg/K and choose the effectiveness as the optimisation parameter. The model takes the inlet temperature and flow rate on the water and glycol sides as input and computes the outlet temperatures.

We estimate the effectiveness by minimising the objective function

\[ \varphi_{\text{ex}} = \sum \dot{m}_{\text{w}} (T_{\text{out},\text{w}}^{(s)} - T_{\text{out},\text{w}}^{(m)})^2 + \sum \dot{m}_{\text{gly}} (T_{\text{out},\text{gly}}^{(s)} - T_{\text{out},\text{gly}}^{(m)})^2, \]  

where \( \dot{m} \) is the mass flow rate and \( T_{\text{out}} \) the outlet temperature. Superscripts \( s \) and \( m \) denote simulated and measured values respectively and subscripts \( \text{w} \) and \( \text{gly} \) refer to the water and glycol sides respectively. The summation again...
runs over all time steps in the simulation. Equation (3) ensures that observations where the flow rates are high receive corresponding more weight in the calibration and at the same time does not discriminate between positive and negative simulation errors. Minimising the objective function for each of the heat exchangers we obtain an effectiveness of 0.913 for the new heat exchanger and 0.911 for the old heat exchanger. In Fig. 3 we show the simulated accumulated energy delivered on the water side of the two heat exchangers and compare to the measured values.

During times with non-zero flow, the mean absolute temperature simulation error on the water side is 2.6 °C for the old heat exchanger and 1.8 °C for the new heat exchanger.

3.3. BTES

The borehole thermal energy storage is modelled as a vertical U-tube ground heat exchanger (type 557b). The storage volume is 19,000 m³ and the boreholes are 45 m deep. The storage contains a total of 48 2U borehole heat exchangers connected in strings of 6 boreholes in series. The fluid circulated through the pipes is water so we set the specific heat to 4.19 kJ/kg/K and the density to 1000 kg/m³. The thermal dynamics of the storage fluid depend on the borehole properties on short time scales and the soil properties on long timescales. The boreholes are parameterised by the borehole thermal resistance $R_b$ while the storage volume is characterised by the soil heat capacity $C$ and the
thermal conductivity $\lambda$. The storage volume is stratified with six identified lithological layers with estimated thermal parameters given in Table 2 [8]. The model does not allow for stratification of the storage volume, but does allow stratification of the surrounding volume. Hence we apply the values in Table 2 for the surroundings and use an effective value for the storage itself. In order to allow the model to adjust to both short and long timescales we choose the borehole thermal resistance and the effective heat capacity of the storage as model parameters. Inside the storage volume we set the effective thermal conductivity equal to the weighted average of the values from Table 2. We note that although in principle the storage specific heat is known, we must allow some minor variation to take into account uncertainties in the storage geometry which cannot be controlled in the model.

The initial storage temperature for the simulation is calculated by preheating the storage with a sinusoidal forcing function

$$T_{\text{BTES}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} + \frac{T_{\text{max}} - T_{\text{min}}}{2} \sin(\omega(t + \theta)),$$

where $T_{\text{max}}$ and $T_{\text{min}}$ are the maximum and minimum storage temperatures during the preheating period, $\omega = 2\pi/365$ if the time is measured in days and $\theta$ is a phase shift describing when the heating began. The simulation starts at $t = 0$, i.e. the preheating occurs at $t < 0$. We set $T_{\text{min}} = 15 \degree C$, $T_{\text{max}} = 45 \degree C$ and $\theta = 210$ days ensuring the highest storage temperature at the end of August.

We estimate the storage heat capacity and fluid to ground resistance by minimising the objective function

$$\varphi_{\text{BTES}} = \sum \dot{m} \left( T_{\text{out}}^{(\text{s})} - T_{\text{out}}^{(\text{m})} \right)^2,$$

where $\dot{m}$ is the fluid mass flow rate and $T_{\text{out}}^{(\text{s})}$ and $T_{\text{out}}^{(\text{m})}$ are the simulated and measured fluid outlet temperatures respectively. The calibration yields a storage specific heat of 2.00 MJ/m$^3$/K and borehole thermal resistance of 0.0180 m $\cdot$ K/W. The accumulated energy extracted from the storage is shown in Figure 4. The average absolute temperature simulation error is 0.85 $\degree C$.

The estimated heat capacity is within 2% of the value obtained as the weighted average of the values in Table 2, indicating good agreement with the long term dynamics determined by the soil. The estimated borehole thermal resistance is somewhat lower than would be expected for a 2U heat exchanger. Type 557 is an implementation of the Duct Ground Heat Storage Model (DST) developed by Hellström [9]. The model is based on a steady flux assumption which may not provide accurate predictions for short timescales when the thermal power varies [10–12]. When minimising the objective function, simulation errors on short timescales are absorbed into $R_b$ since the borehole thermal resistance influences the short term fluid temperature response.

### 3.4. Heat pump

The BTES is discharged through a heat pump in order to achieve sufficiently high outlet temperatures. We model the heat pump as a normalised water-to-water heat pump (type 927) which utilises a user specified file with performance data to predict outlet temperatures. The data file specifies the heat pump capacity and power draw for different inlet temperatures. These values are interpolated during the simulation to determine the capacity $\text{Cap}$ and power $P$ for the given inlet temperatures. From these interpolated values the outlet temperatures are calculated from

$$P - \text{Cap} = \dot{m}^{(\text{src})} \cdot c_p \cdot \left( T_{\text{out}}^{(\text{src})} - T_{\text{in}}^{(\text{src})} \right)$$

$$\text{Cap} = \dot{m}^{(\text{load})} \cdot c_p \cdot \left( T_{\text{out}}^{(\text{load})} - T_{\text{in}}^{(\text{load})} \right),$$

where $\dot{m}$ is the mass flow rate, $c_p$ is the specific heat capacity, and $T$ is the temperature.
where $\dot{m}^{(\text{src})}$ and $\dot{m}^{(\text{load})}$ are the fluid mass flow rate on the source and load sides respectively, while $T^{(\text{src})}_{\text{out}}$ and $T^{(\text{load})}_{\text{out}}$ are the outlet temperatures on the source and load sides. Since the simulated outlet temperatures are based on interpolating user specified performance data, we cannot calibrate the heat pump in the same manner as the preceding components by minimising a function of model parameters. Instead, we calculate the heat pump power and capacity from Eqs. (6) using measured operational values of the source and load side temperatures and flow rate. Based on the resulting scattered point set, a Delaunay triangulation is applied followed by linear interpolation to a set of query points, which are written to a data file for use in the TRNSYS model. In Figure 5 we compare the measured and simulated energy delivered on the load side of the heat pump. The average absolute temperature simulation error is 6.7 °C over the full simulation period.
3.5. Conventional production, tanks and total model

The final model is constructed by connecting all components to the storage tanks. Since the aim is to simulate the interplay between variable heat production from the solar collectors, short term storage in the tanks and long term storage in the BTES, the heat production from the electrical boiler, natural gas engine and natural gas boiler are not simulated separately. Instead, these components are considered collectively as simply conventional production. If the forward temperature to the district heating network is too low, one or more of these conventional production units must be turned on. The main interest here is the amount of thermal power delivered from the conventional sources. Which source is used in a given situation depends on the prices of heat, electricity and fuel, however this analysis can be performed separately and does not impact the physical model considered here, to the extent that we assume all conventional sources may be controlled precisely in terms of the delivered power. In the TRNSYS model we handle the conventional sources by separating out part of the return flow from the district heating network and reinject it to the forward flow at a set temperature of $T_{\text{set}} = 95 \, ^\circ\text{C}$ (see Fig. 6). The total thermal power delivered from the conventional sources is determined from the operational data so the necessary flow may be calculated from

$$ P_{\text{conv}} = \dot{m}_{\text{conv}} \cdot c_p \cdot \left( T_{\text{set}} - T_{\text{DH}}^{(\text{ret})} \right), $$

where $T_{\text{DH}}^{(\text{ret})}$ is the return temperature from the district heating network and $\dot{m}_{\text{conv}}$ the calculated flow. The remaining flow is delivered to the tanks in a different way depending on the season. During summer the two tanks are connected in series with the return flow from the district heating network directed to the bottom inlet of the small tank (see Fig. 6a). The top outlet of the small tank is connected to the bottom inlet of the large tank and the top outlet of the large tank feeds back to the district heating network. The flow between the tanks is calculated from the mass balance given the flow of the remaining components. During winter the district heat return flow is directed to the bottom of the large tank, while the small tank is used as a cold storage for discharging the BTES (see Fig. 6b). Both tanks are modelled using type 60, each with ten temperature nodes.

The model is driven by reading in the operational flow for the solar collectors, heat exchangers, BTES, heatpump and district heat return. Additionally, the ambient temperature and incident radiation for the solar collectors as well as the thermal power from the conventional sources and return temperature from the district heating network are supplied to the model.

4. Results and discussion

In order to quantify the performance of the total model we compare the predicted and observed heat delivered to the district heating network (see Fig. 7). The final error in the predicted energy is $2.75 \, \text{GWh}$ corresponding to a
simulation error of 7.1%. As is apparent in Figure 7 the simulated energy and hence the simulated forward temperature to the district heating network is consistently underestimated. The average absolute temperature prediction error for the forward temperature is 9.6 °C.

In Table 3 we list the simulation errors of the model components when running the full system simulation and compare to the simulation errors found during the calibration step. The difference between these values reflects the propagation of simulation errors in the final model when simulated outlet temperatures from one component are passed as inlet temperatures to the next.

Table 3. Comparison of simulation errors for the final model and single component calibrations. Since the net energy extracted from the BTES on an annual basis is small, charging and discharging are separated.

<table>
<thead>
<tr>
<th>Component</th>
<th>Final model error</th>
<th>Calibration model error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[MWh]</td>
<td>[%]</td>
</tr>
<tr>
<td>New solar collectors</td>
<td>530</td>
<td>11.3</td>
</tr>
<tr>
<td>Old solar collectors</td>
<td>195</td>
<td>6.3</td>
</tr>
<tr>
<td>New heat exchanger&lt;sup&gt;a&lt;/sup&gt;</td>
<td>620</td>
<td>13.0</td>
</tr>
<tr>
<td>Old heat exchanger&lt;sup&gt;a&lt;/sup&gt;</td>
<td>493</td>
<td>14.5</td>
</tr>
<tr>
<td>BTES (charging)</td>
<td>49</td>
<td>13.8</td>
</tr>
<tr>
<td>BTES (discharging)</td>
<td>22</td>
<td>7.6</td>
</tr>
<tr>
<td>Heat pump&lt;sup&gt;b&lt;/sup&gt;</td>
<td>190</td>
<td>18.6</td>
</tr>
</tbody>
</table>

<sup>a</sup>: Energy transfer across the heat exchanger  
<sup>b</sup>: Energy delivered on the load side

In general, the full model produces higher errors for individual components as expected. When considering the relative errors we further observe an evening out of the simulation errors for the full model compared to those found in the calibration step. When building a model in this way, the final model is roughly speaking only as good as the worst performing component. Further improvements to the final model could potentially be made by considering the energy flow between components in more detail. In the present case the heat pump seems an obvious candidate for further scrutiny, as it demonstrates the highest relative simulation error in the final model.

5. Conclusion

We have applied a modular approach to develop a TRNSYS model based on operational data for a district heating plant using inverse modelling to identify key component parameters. The model is driven by recorded values of flow
rates for individual components as well as ambient temperature and incident radiation for the solar collectors. We find that the full system model assembled from the separately optimised components yields a prediction error of 7.1% in terms of the heat delivered to the district heating network. In future work we propose to use the final model to evaluate alternative control strategies by passing different flows to the forward model, and for analysing the impact of different weather scenarios by passing alternative values for the collector irradiation and ambient temperature.

References


