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Dynamic model for large scale hot water storage tank

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ABSTRACT

Due to the growing share of intermittent renewable energy sources (RES), the requirement for flexibility in the energy system is increasing to balance the generation and demand of electricity. It has been well recognized that Combined heat and power plants (CHPs) can contribute towards improved flexibility in the energy system. Thermal energy storage (TES), using hot water as working fluid, is a commonly integrated in CHPs, which allows for decoupling of heat and electricity generation. It has been verified that proper control of the operation of TES can improve the flexibility provided by CHP. The development of advanced control system relies on accurate dynamic modeling of TES. In this work, a one-dimension (1D) dynamic model for large scale TES is developed in Dymola, based on mass and energy balances. It is validated against the operational data from a real CHP plant. Results show that the model can capture the dynamic variation in the operation of the TES energy content with maximum deviations of 6.5% from the maximum value.

Keywords: Combined heat and power plants (CHP), Thermal energy storage (TES), flexibility, dynamic model, large scale.

NONMENCLATURE

Abbreviations	
CHPP	Combined heat and power plants
RES	Renewable energy sources
TES	Thermal energy storage
Symbols	
e	Euler number (natural logarithm)
S	Value of Sigmoid function

1. INTRODUCTION

Due to the high share of intermittent Renewable Energy Sources (RES), the requirement for flexibility in the energy system is increasing [1]. Flexibility is defined as the ability of the system to adjust to varying supply and demand over time. Towards ensuring flexibility in energy systems with high share of RES, important role goes to combined heat and power plants (CHPP) [2]. They provide both district heating and electricity, and their generation is coupled, which limits the flexibility in operation. Common practice nowadays is to implement thermal energy storage (TES) system with CHPP, which allows for decoupling of heat and electricity generation to some extent [2].

While there are many forms of TES, the most widely applied one with municipal CHP plants is hot water storage tank (HWST), due to its multiple advantages [3]. It is cost-effective, has high thermal capacity, and has long track of successful uses. Thermal energy storage is cost effective compared to electricity storage.

HWST are used generally to balance heat demand and shave peaks of demand. They allow for decreasing operation costs and decreased emissions [4]. Currently electricity prices are highly volatile [5]. Due to this, there is growing potential to adjust operation and make higher use of the capacity of the installed TES system. To be able to assess the transient operation of TES system within CHPP, dynamic model is essential. Dynamic models allow for analysis of the transients and the time constants of the system.

HWST have complex operation which includes phenomena such as stratification [6]. All the processes within HWST cannot be solved with mathematical equations without simplifications of the system and some assumptions [6]. In modeling works, there is always a trade-off between model complexity and accuracy. Towards analyzing the transient operation of the tank, there is the need to have satisfactory accuracy while been able to connect the model with other components and with control system [7].

While TES have been interesting research topic with numerous publications, works dedicated to HWST are rather scarce [8]. More of the effort have been concentrated towards solar combined and systems for residential buildings, which leaves the applications for CHPP significantly limited. Overview of developed models for TES systems are shown in works [8] and [9]. The modeling approach used affects significantly the estimated energy content in the tank, and with it, the potential benefits for the system [9]. Modeling features and algorithm for assessment of models is proposed in [6]. Mostly the classification is by their dimensionality and the general assumption of the behavior. In [7], 1D model is proposed. Validations are made with published experimental data from small scale tanks.

Based on the literature review and the recent reviews, it is notable that there are very few works on large scale HWST validated with operational data[10]. To the best of knowledge there is no published dynamic model for large scale tank used with utility CHP plant. This is very important topic due to the high potential of CHPP to provide flexibility to the system and also improve own competitiveness by increasing revenues by generating electricity in the periods of the day with higher prices.

The main contribution of this work is the development of simplified dynamic model, which is able to accurately capture the behavior of the analyzed plant. With this type of model, we can analyze the operation of the plant in different scenarios and identify opportunities for improvements in operation.

Methodology used in this work is shown in Section 2, by describing the analyzed system and the developed model. The obtained results and the validation approach are shown in Section 3. Conclusions and future work are shown in Section 4.

2. METHODOLOGY

2.1 Case study system

The analyzed tank is from municipal CHP plant in Sweden. The key parameters of the analyzed tank are shown in Table 1.

The tank is used extensively throughout the operation year. Its operation is coordinated based on weather forecast (and heat demand based on it), prediction about electricity prices and unforeseen changes in the supply and/or demand in the energy system. The tank is operated in two modes – charge and discharge.

Table 1 - Key tank properties

Parameter	Value	Parameter	Value
Volume	25500 m3	Tank Energy	1100 MWh
Diameter	26 m	Max charge rate	100 MW
Height	50 m	Max flow volume	0.5 m^3/s

In charge mode, hot water supplied from the CHP enters the tank from the top part, and colder water is extracted from the bottom part. In this way, the energy content of the tank is increased. For discharge mode, it is opposite. Hot water is extracted from the top of the tank, while cold water enters from the bottom, during which the energy of the tank is decreased. Scheme of the analyzed plant is shown in Fig. 1.

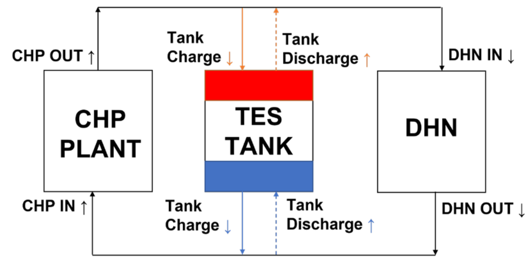

Figure 1 - Tank operation logics scheme

2.2 Model description

The model is developed in the software Dymola, which uses the programing language Modelica. The modeling approach is acausal, which allows for faster model development and easier model reuse.

Mass and energy balances are written for the tank. The tank is divided in 20 equal control volumes. The number is set to 20 due to the number of measurements present in the analyzed case study and they are used for the energy content of the tank estimation. Water properties, calculated as function of temperature are calculated according to [11].

Discharging of the tank is described as:

$$Q_{discharging} = Q_{out} - Q_{in} = Q_{top.tank} - Q_{DHN.return} = \dot{V}\left(\rho_{top.tank} \cdot h_{top.tank} - \rho_{DHN.return} \cdot h_{DHN.return}\right) \quad (1)$$

Charging of the tank is described as:

$$Q_{charging} = Q_{in} - Q_{out} = Q_{CHP.charge} - Q_{bottom.tank} = \dot{V}\left(\rho_{CHP.charge} \cdot h_{CHP.charge} - \rho_{bottom.tank} \cdot h_{bottom.tank}\right) \quad (2)$$

where: Q is heat [kW], $\dot{V}$ is volume flow [m^3/s], ρ is density [kg/m^3], and h is enthalpy [kJ/kg] for the analyzed inlet and outlet streams in the tank.

The temperature change at each node is calculated by:

$$\frac{dT_i}{dt} = \frac{\dot{m}_{i_{in}} h_{i_{in}} - \dot{m}_{i_{out}} h_{i_{out}} + HT_{(i+1)\to i} - HT_{i\to(i-1)} - Q_{losses}}{Cp_i \cdot V_i \cdot \rho_i} \quad (3)$$

where: T is temperature in [K], m_i is mass flow for the i-th node in [kg/s], subscripts indicate in and out flows, h_i is enthalpy for the i-th node in [kJ/kj], HT is heat transfer and its direction is indicated in the subscript, Q_{losses} is heat losses to the environment from the tank, C_p is the specific heat capacity for water [kJ/(kg·K)], V is volume of each node [m^3], and ρ is density of water [kg/m^3].

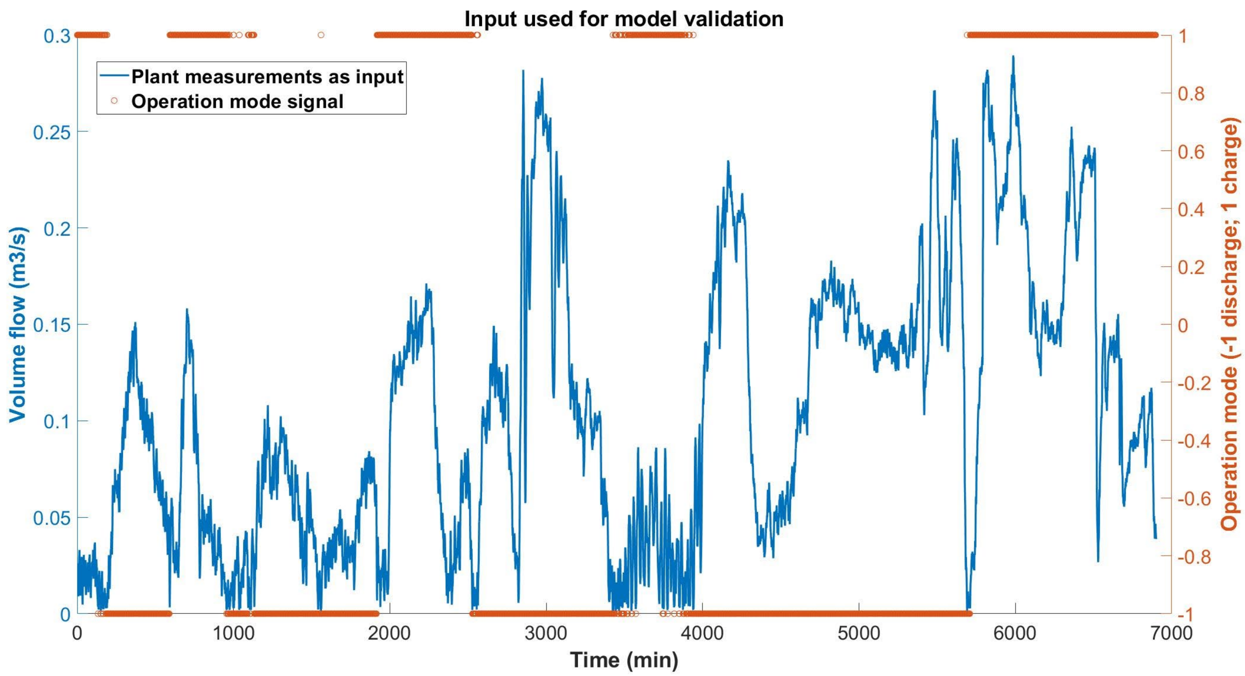

Figure 2 - Inputs used for validation - operation mode and volume flow used

The energy content in the tank is calculated by:

$$E = \sum_{i=1}^{20} Cp_i \cdot m_i \cdot \Delta T_i = \sum_{i=1}^{20} Cp_i \cdot V_i \cdot \rho_i \cdot \Delta T_i \quad (4)$$

where: ΔT_i is the temperature difference between the temperature in the i-th node and a predefined temperature as the minimum operating temperature of TES.

The model can simulate charge and discharge operation logics switch with the use of sigmoid function. The equation used for sigmoid function is shown in Eq.5:

$$S(x) = \frac{1}{1+e^{-x}} \quad (5)$$

The volume flows in and out of the tank are assumed to be equal. During charge mode, the direction of flow is taken from the top towards the bottom, while

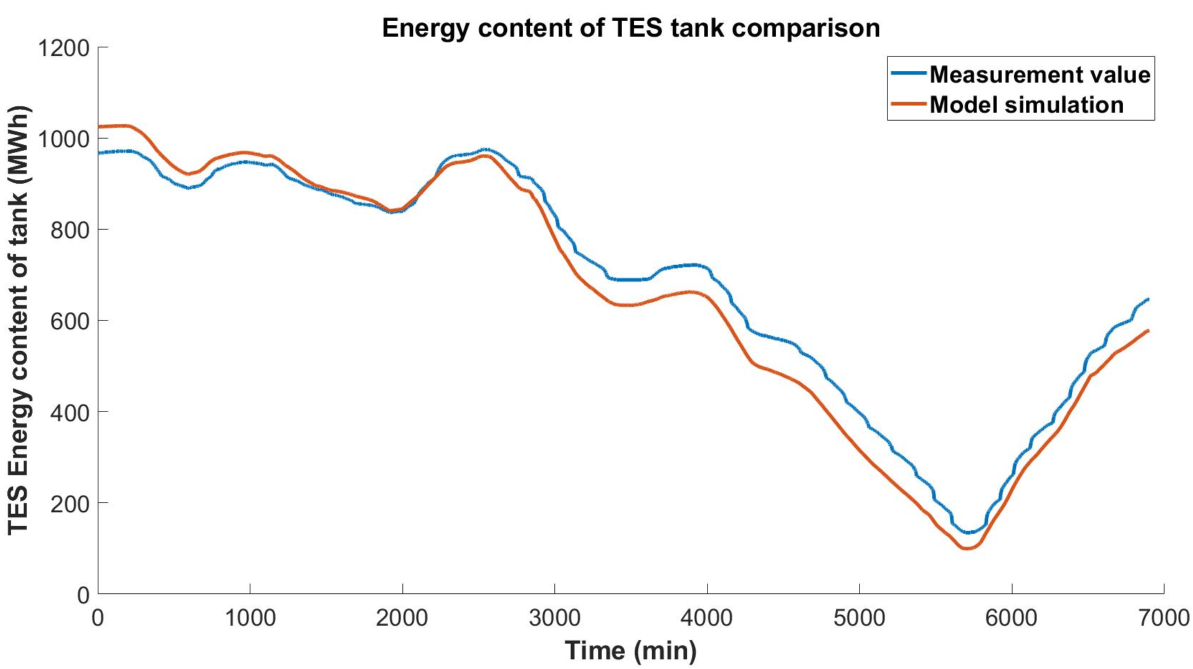

Figure 3 – Validation results for the energy content of the analyzed tank

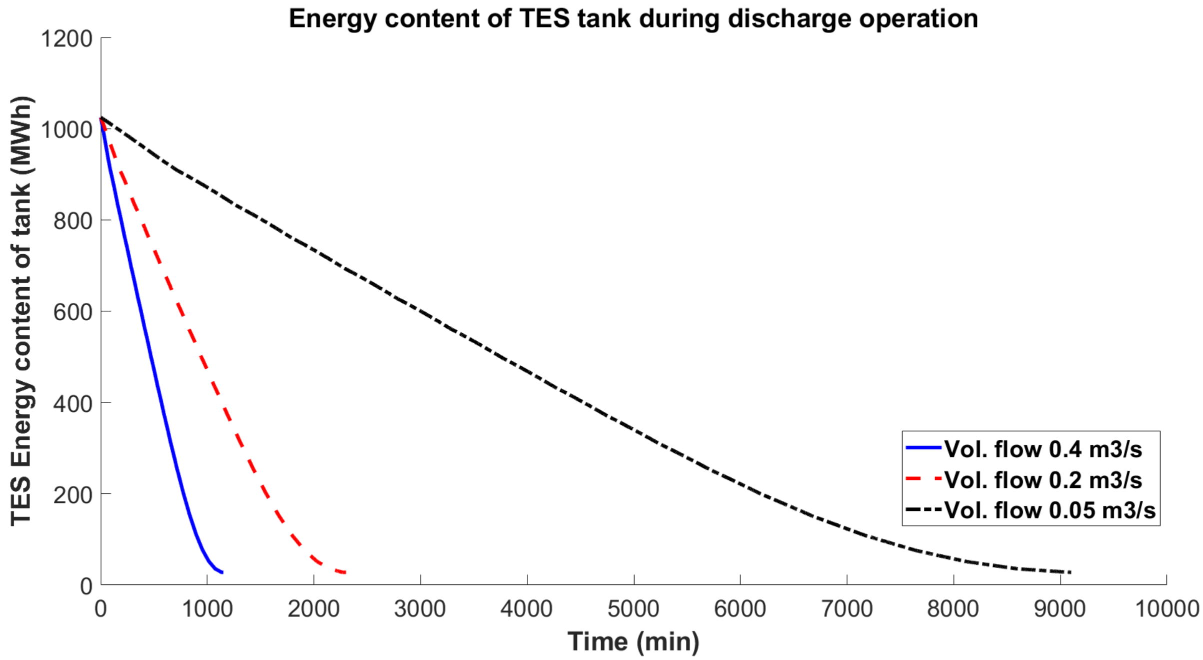

Figure 4 – Discharge operation for the analyzed tank with 3 different volume flows

during discharge mode is in the reverse order. Heat transfer is calculated to the next control volume based on the temperature difference between neighboring control volumes.

3. RESULTS

3.1 Validation

The model is calibrated and validated by using plant operation data. The validation is done by using chosen input variables in the model from the plant measurements, and output is compared.

As inputs are used: tank operation mode (charge/discharge), volume flows and temperatures for streams in and out of the tank. The inputs used for validation are shown in Fig. 2 and the results in Fig. 3.

The model can capture the trends of the tank operation. The simulation for validation is run for period of 414000 s, with extractions at intervals of 60s. During this period, the tank is operated within the operation range from 100 to 1000 MWh. There are multiple charges and discharges with different volume flows used.

The maximum calculated deviation during validation is 80 MWh. This represents about 7.2% from the maximum charge rate of the tank at 1100MWh.

3.2 Model use for transient performance assessment

The validated model is used to assess the transient operation of the HWST during discharge and charge operation. Both discharge and charge operations are analyzed with 3 different values for volume flow used and its impact on the required time for full discharge and charge operation.

The discharge operation is shown in Fig. 4, the time required for it is summarized in Table 2. The charge operation is shown in Fig. 5, the time required for it is summarized in Table 3.

Table 2 – Time required for discharge operation

Case #	Volume flow (m^3/s)	Discharge time (s)	Discharge time converted (days and hours)
1	0.05	546000	151.7h, 6.3 days
2	0.2	138000	38.3h, 1.6 days
3	0.4	69000	19.2h, 0.8 days

Table 3 – Time required for charge operation

Case #	Volume flow (m^3/s)	Charge time (s)	Charge time converted (days and hours)
1	0.05	651000	180.8h, 7.5 days
2	0.2	165000	45.8h, 1.7 days
3	0.4	81960	22.8h, 0.9 days

From the obtained results, it is obvious that the discharge and charge times are dependent on the volume flow used. The higher the volume flow used, the shorter the discharge and charge times.

It can also be noticed that for each volume flow used, the charge time is higher than the discharge time for the same change in energy content in the tank. This can be explained by the fact that during the charge process the temperature (and the energy content difference) from the inlet and outlet streams in the tank is lower, and it

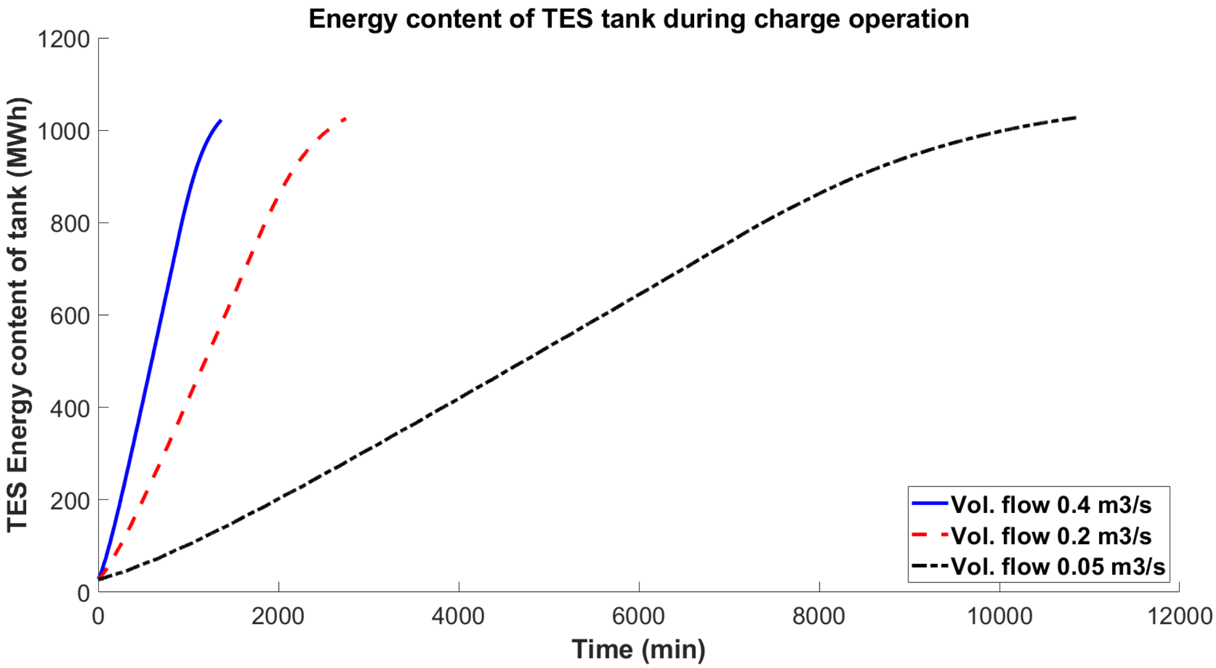

Figure 5 – Discharge operation for the analyzed tank with 3 different volume flows

requires more time for the same change in energy content within the tank.

4. CONCLUSIONS

In this work, dynamic model of large-scale hot water storage tank (HWST) applied in combined heat and power plant (CHPP) is presented. The model accuracy is validated with operational data from the analyzed plant. The model can capture the trends of change of the analyzed tank. The deviation is within 7.2% of the maximum value of energy content of the tank. The validated model is used to assess the time required for full discharge and charge operation of the analyzed tank for different volume flows.

The simplified configuration of the model allows for it to be combined with other components from CHPP for whole system simulation. Using this model as a basis for developing advanced controller, such as Model Predictive Control, is listed as future work.

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