Comparison of Two Simulation Methods for the Technical Feasibility of a District Heating System Using Waste Heat from a Copper Plant with Thermal Storage

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Abstract

Prior studies have noted that modelling and simulation approaches provide useful assistance in designing new generation district heating systems to deal with the increasing complexity of technologies. The available models and tools cover wide varieties in terms of technologies, model complexities, etc. In order to identify the applicability of different modelling methods for certain cases, the present study compared an energy planning tool with a dynamic simulation method for a district heating system using waste heat from a copper plant with thermal storage. The results showed the two methods predicted similar usage of heating energy from sources and demand for the case with short-term thermal storage, especially in cold months. However, large discrepancies were observed when including long-term thermal storage.

Introduction

A recent study has shown that heating production accounts for more than half of global final energy consumption and that 45% of global energy use for heating came from fossil fuels (Eisentraut & Brown, 2014). In order to reduce fossil fuel consumption, over 190 countries signed up for the global agreement on mitigating climate change during the 2015 Paris Climate Conference (also known as COP21). Meanwhile, the EU holds the ambition to increase the share of renewable energy sources (RES) to at least 20% of the whole energy consumption by 2020. New generation district heating (DH) infrastructures play an important role in renewable heating technologies to support this energy transition. New generation district heating systems (DHS), namely the fourth generation, are labeled as low-temperature district heating systems (with a water temperature of 30-70 °C). They provide flexibility on the utility of low-grade heating sources, such as heat recycled from chillers, industrial surplus, geothermal energy, solar thermal energy or even heat produced by consumers. It is possible for DH to serve some low heat density areas (e.g. areas with low energy buildings) (Lund et al., 2014). New generation district heating systems encourage the use of thermal energy storage (TES) to resolve the discrepancy between heating demand and low-grade heating sources in both the short term and long term. TES and generation systems can be centralized and decentralized. Thus, the energy flow interaction between generation and distribution networks, and even among buildings themselves, can be bidirectional in order to share energy (Ancona, Branchini, De Pascale, & Melino, 2015). In short, more system components and interactions are involved in new generation DHS.

Since DH infrastructures tend to be more complex than previous generation methods, designers face challenges in the implementation of new technologies. A district heating system using surplus heat from industrial processes or from cooling processes in commercial buildings requires detailed dynamic performance investigation and planning because the surplus heat is not controlled from the demand side, even if it were available during the whole year (Lund et al., 2014). The complexity of implementing new generation DHS is also increased since their main supply sources are renewable energy sources. Compared to traditional fossil fuel based technologies, one major characteristic of RES is that although there are a wide variety of sources, their use is dependent on local availability. Therefore, designers have to develop solutions to identify potential supply sources and subsequently dispatch them to end-users on a case by case basis. Sometimes novel technologies have to be implemented. For example, in low heating density areas, DHS need to implement low-temperature district heating technology that is still in development stage in order to be economically competitive. Furthermore, the fluctuating production from RES requires storages or alternative supply sources as well as superior management. The consideration should also be included in the design of DHS.

As a consequence of the increasing complexity in new generation DHS, traditional methods of designing DHS become more and more inapplicable. Thus, analysing the performance of new generation DHS requires computational tools to model defined systems in order to answer design questions. A wide range of modelling approaches and simulation tools are available to analyse the performance of district heating systems (Allegrini et al., 2015). They are capable of conducting simulation, operation and investment optimization in different resolutions and horizons in terms of time and geographical scale (Connolly, Lund, Mathiesen, & Leahy, 2010). These approaches can be classified, so to speak, as having two ends. One end is energy planning tools (e.g. EnergyPLAN, energyPRO) designed to support decision making for recognizing energy flows and comparing different design solutions. These planning tools usually adopt macroscopic models for national and regional scale. The other end are detailed multi-disciplinary tools, such as TRNSYS and Modelica, which are usually used to analyse community energy systems (Connolly et al., 2010). However, overlap in the analysis scale for the utilization of modelling approaches has been observed in several studies. Østergaard reviewed 95 peer-reviewed journal articles applying EnergyPLAN between 2003 and 2014 (2015). Thirteen of them are local scale analysis, such as small neighbourhoods or even a small group of buildings. Therefore, model complexity is another key consideration to simulate district heating systems properly. Less complexity generally means more assumptions are included in models, yet these assumptions cannot be readily seen (Keirstead, Jennings, & Sivakumar, 2012). More complex models also require more data, which is not always available. To the best of the present authors' knowledge, few studies have clarified the proper model complexity required for different purposes of analysis.

In response to the challenges in both design and the aid of modelling and simulation of new generation DHS, the present study first provides a general overview of modelling approaches and simulation tools for DHS in the next section. Two main categories are introduced, namely energy planning tools and dynamic simulation tools. This paper then compares the two methods of analysing energy balance through a case study for a district heating system located in Chifeng city, Inner Mongolia, China. The DHS supplied space heating and domestic hot water through solar thermal energy and industrial waste heat from a copper plant. Main design parameters are provided followed by descriptions of the two methods and sub-models. Results obtained by the two methods are presented focusing on analysing the amount of heat recovered from the industrial process and stored in the thermal storage. Possible reasons for the discrepancies between the two methods and application suggestions are discussed in the last part of this paper.

Modelling and Simulation of DHS

As illustrated in the previous section, modelling and simulating a DHS can be conducted via a variety of approaches, which can be catagorized according to many criteria. Valdimarsson (1993) classified models of DHS in four categories, namely by type (microscopic or macroscopic), by method (dynamic or steady state), by approach (physical or black box) and by usage (design or operation). The classifications are straightforward, except for the type category. Here, the concepts "microscopic" and "macroscopic" define whether DHS is studied in detail in both time and space, or whether the entities of DHS are lumped into several model blocks. Olsthoorn et al. (2016) considered DHS models as deterministic models and stochastic models. Deterministic models represent physical phenomena such as the degree-day method or energy balance equations, whereas stochastic models mainly use mathematical approaches e.g. statistical regression and artificial neuro networks. As such, simulation tools in which these different models are embedded also have many categories and should be applied to different simulation purposes. Tools for energy planning and dynamic energy simulation are the two main categories.

Energy planning tools are designed to analyse how to integrate renewable energy into current energy systems from the technical, economic and social points of view. Energy planning tools often focus on the analysis of large-scale energy schemes, e.g. national, regional or even global. Thus, they usually use steady state methods or stochastic models since the two methods consume much less computational resources and require less data input. Most energy planning tools not only consider building heating or electricity sectors, but also industrial use and transportation. In terms of long-term scenario analysis, time spans are typically 20-50 years. It is important to note though that energy planning tools were not originally developed to investigate the performance of DHS. However, since DHS has received growing interest as a possible measure to approach a low carbon emission society, most energy planning tools have embedded DHS as one component. One of the typical energy planning tools is EnergyPLAN, developed and maintained by Aalborg University in Denmark. It can model all thermal, renewable, storage/conversion, transport and relevant costs (Aalborg University, n.d.). It balances production with demand for all sectors under certain optimization strategies. It operates on an hourly basis for a whole year analysis.

There also some energy planning tools that are specifically designed for district heating projects. For example, the energyPRO tool is used to investigate a single thermal or CHP power plant, and can also integrate other RES generation and energy storage technologies to supply district heating (EMD International A/S, n.d.). Compared to EnergyPLAN, energyPRO is designed to model and optimize the operation of smaller and local energy systems and plants with a higher level of detail (Jensen, Lund, & Connolly, 2013). Jensen et al (2013) applied both EnergyPLAN and energyPRO to analyse the integration TES with a heat pump and electrical boiler. The results showed similarities in only some points because the TES in EnergyPLAN could not be charged by a heat pump or electric boiler.

The other type of simulation tools for DHS is dynamic simulation tools, which can be used for detailed DHS energy modelling. Dynamic simulation tools simulate the performance of an energy system by breaking it down into individual components. They typically simulate a given designed DHS in hourly/sub-hourly time-steps for one year or even less. Many commercial software or general programming tools are available to conduct dynamic simulation for DHS, e.g. TRNSYS, Modelica, MATLAB/Simulink, etc. However, most of them are not primarily DHS simulation tools. For example, TRNSYS (University of Wisconsin-Madison, 2013) was originally developed in 1975 to simulate a solar hot water system and has been used as an extensible software tool to simulate thermal and electrical systems in general. As most dynamic simulation tools are meant for detailed energy system simulation, they are not always capable of simulating building demands together with district heating distribution networks and generation simultaneously. At present, the common approach is to simulate building demands externally and then import them as an input to heat exchangers between distribution networks and consumers (buildings) to represent the amount of heat required (Papillon & Paulus, 2013; Vaillant Rebollar, Himpe & Janssens, 2014). Unlike TRNSYS, Modelica is an acausal equation-based programming language. Different domains including mechanical, thermodynamic, hydraulic, biological, and control applications can be described and connected by models in Modelica (Fritzson, 2011). The code in Modelica is highly reusable, and therefore efforts for the development of new models in Modelica are significantly reduced compared to TRNSYS or MATLAB/Simulink. Several Modelica libraries oriented in district-level applications are under development through the IEA EBC Annex 60 and many other developers.

Case study: Copper plant DHS in Chifeng (China)

In line with the purpose of the present study, the simulation tools should 1) have the flexibility to specify the combination of different supply sources as well as their capacities and 2) be at least hourly-based with an analysis period equal to or larger than one year. Along with the above criteria, this study adopted an analytical steady simulation (M1) by using an energy planning tool and a dynamic physical simulation method (M2) by using the Modelica language with model components from free open-source libraries. The investigated case study represented an on-going renovated district heating project for a copper plant in Chifeng, Inner Mongolia, China (42°15'N 118°53'E).

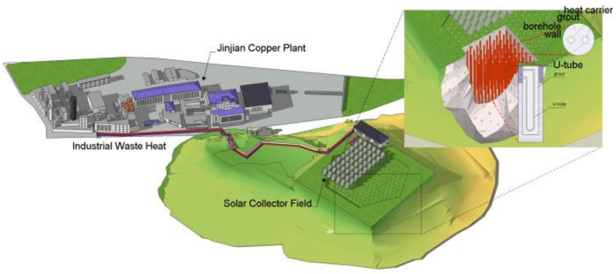

Figure 1: Design sketch of the project.

Figure 1 illustrates the scheme of the designed system. Excess heat from the copper plant served as the main heating supply source. The system includes an acid/water heat exchanger to recover the waste heat from the 98% H_2SO_4 cooling process as Figure 2 shows. The inlet and outlet acid temperature are 100 ºC and 80 ºC. Another water-to-water heat exchanger is used to transfer heat from the recovered waste heat to other heating systems. The outlet acid temperature is necessary to be kept constant according to the industrial process requirements. A branch loop to cooling tower is added to ensure the requirements. The inlet temperature of the water-to-water heat exchanger is controlled to be 70 ºC constantly.

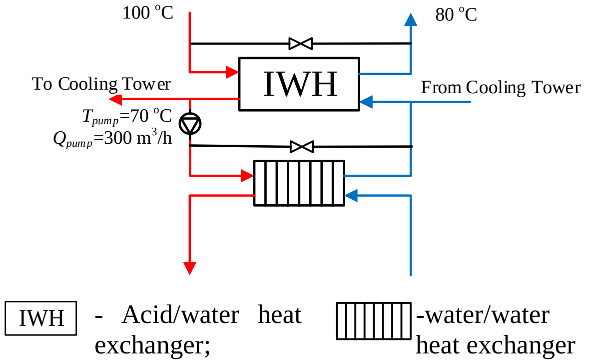

Figure 2: System diagram of the industrial waste heat recovery process.

Solar thermal collectors with a total effective area of 1002 m^2 represented another heat source. A borehole thermal energy storage was located directly below the solar field. Other design parameters for the newly built district heating system are shown in Table 1. Each component in the district heating system was equipped with a heat exchanger to transfer heat to the main district heating network and had independent hydraulic systems. The designed district heating system supplied space heating and domestic hot water to buildings inside the copper plant. Table 2 summarizes the main properties of buildings connected to the district heating network. Space heating was served between the 16th of October and the 15th of April the following year, the so-called heating season. Domestic hot water was available all year round.

Table 1: Design parameters for the district heating system

Parameters	Value
Industrial waste heat (IWH)	
Capacity	32.4 GWh/year
Nominal flow rate	30 m^3/h (non-heating season)
	300 m^3/h (heating season)
Solar thermal system (STS)	
Area of collectors	1002 m^2
Tilt angle	55°
Capacity	0.416 GWh/year
Buffer tank volume	0.5 m^3
Seasonal thermal energy storage (STES)	
Storage type	Single U-tube borehole
Storage volume	519,615 m^3
Storage capacity	2944 MWh/year
Number of boreholes	468
Drilling depth	80 m
Borehole diameter	150 mm
Distribution network	
Supply temperature	60 °C
Return temperature	50 °C

DHW temperature	60 °C
Circulating flow rate	30 m^3/h

Table 2: General building properties

Buildings	Total area (m^2)	Storeys	WWR[1]
Office 1	4230	3	0.34
Dormitory1	2988	4	0.30
Multi-use building	10390	6	0.26
Laboratory	913	3	0.25
Office 2	495	2	0.17
Dormitory 2	217	1	0.10

Models description

Energy planning method

This study adopted EnergyPLAN (version 12.4) to model the designed district heating system and then simulated by using the energy planning method. EnergyPLAN is a deterministic model to simulate the energy planning strategy in a one-year time period with a time step of one hour. It is based on analytical programming where no iterations or dynamics are involved. Therefore, the calculations of models are seconds-based. It aggregates annual demands and supplies separately in different energy sectors.

Inputs required by EnergyPLAN are dimensionless hourly distribution and annual maximum capacity for all types of generation, storage, and demands. As such, a constant distribution profile was used for excess heat. The hourly distribution profile of the solar thermal system used the same distribution as the global horizontal radiation from the Chinese Standard Weather Data (CSWD) in Chifeng. Thermal storage in EnergyPLAN only took annual capacity into consideration. Annual heat losses through distribution for the entire district heating system were a constant 10%. The hourly building demand profiles for space heating and domestic hot water were simulated in Modelica. The space heating system was ideally controlled with a heating setpoint of 20 ^{o}C. Details of the models are introduced later in the Modelica section.

Outputs from EnergyPLAN could be energy balances and actual production and/or stored energy, fuel consumption and total costs on an hourly, monthly or yearly basis. This case only used the actual hourly production and stored thermal energy for further analysis.

Dynamic physical method

Modelling and simulations using the dynamic physical method are realized in Dymola (version 2016 FD01), a commercial modelling and simulation environment for the Modelica modelling language. Modelling approaches for the main components, including building thermal model, industrial waste heat, solar thermal system and seasonal thermal storage, are described below.

This study simulated building thermal demands by a lumped element model of the equivalent electric circuit (also known as thermal network model). As shown in Figure 3, one resistance (*R*) represents the heat conduction through the building envelope. A single capacitance *C* represents the thermal mass of the building. Heat transfer by infiltration is reflected by *UA*. Solar and internal heat gains (Q_{solar} and Q_{int} respectively) are connected to the indoor air temperature node T_{in}. Q_{dem} is the amount of heating demand to be supplied to the indoor air temperature node. It is calculated through the radiator model *RadiatorEN442_2* from the *Buildings* library (version 3.0.0).

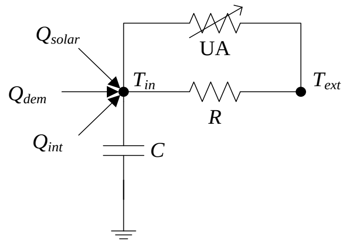

Figure 3: Schematic of building thermal network model.

Thermal characteristics of different elements used in building demand simulation in this study referred to the definition of the baseline building in the Design Standard for Energy Efficiency of Public Buildings (GB50189-2005). U-values for external wall/floor, roof and window were 1.28 W/(m^2·K), 0.77W/(m^2·K) and 3.26 W/(m^2·K) respectively. These thermal characteristics reflected a typical building constructed in the 1980s in the same climate zone.

As for the industrial waste heat model, this study used a heat exchanger with a controlled hot water supply to represent the industrial waste heat. The heat transfer from the acid to the water was omitted. The reason for this simplification was that the excess heat source from the copper plant was quite stable as illustrated in the previous section. Therefore, on one side of the heat exchanger, a mass flow source supplied 70 °C hot water at a constant flow rate. The heat transfer through the heat exchanger was calculated as follows:

$$Q = Q_{\max} \bullet \varepsilon \tag{1}$$

where ε was a constant effectiveness and Q_{max} was the maximum heat that can be transferred. Q_{max} was calculated as:

$$Q_{\max} = \min\left(c_{p1}m_{f1}, c_{p2}m_{f2}\right)\bullet\left(T_{in2} - T_{in1}\right) \tag{2}$$

where m_{f1} and m_{f2} were the mass flow rates of the two sides of the heat exchanger, c_{p1} and c_{p2} are the specific heat capacity of the fluid in the two sides of the heat exchanger, T_{in1} and T_{in2} are the inlet temperature of the fluid in the two sides of the heat exchanger. Here defined

[1] WWR: Window-to-Wall Ratio

side 2 connected to the heat source. Therefore, T_{in2} = 70 ºC

A by-pass was added to make sure supply temperature for space heating and domestic hot water was 60 ± 1 °C using an on/off control valve. The other side of the heat exchanger (side 1) was connected directly to the distribution network.

The solar thermal system consisted of a stratified water tank model from the Buildings library version 3.0.0 (Buildings.Fluid.Storage.StratifiedEnhancedInternalHex) with a built-in heat exchanger inside the tank as short-term thermal storage, a water/water heat exchanger to transfer heat from the tank to the distribution network, a solar collector model (Buildings.Fluid.SolarCollectors.ASHRAE93) and pumps with controls. The solar collector model calculated solar gains and heat losses according to data obtained from ASHRAE93 test procedures. All the technical data was taken from the Solar Rating and Certification Corporation (SRCC) website. For each solar panel, the model discretizes the solar collector volume into i segments. Here i = 3 which was the minimum number required by the solar collector model. Figure 4 shows the energy balance of one solar panel.

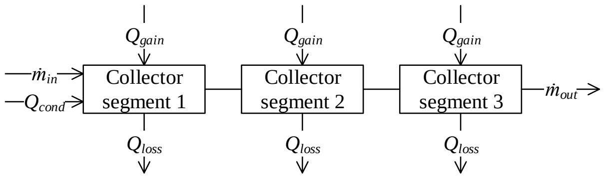

Figure 4: Schematic overview of the nodal energy balance in one solar panel.

Both mass balance and energy balance were considered dynamic behaviours. The tank model and the solar collector model have been validated by their developers as stated in the Modelica Buildings Library Documentation (Lawrence Berkeley National Laboratory, 2017). The heat exchanger connecting the tank and the distribution network was modelled using the same component as in the industrial waste heat recovery model.

Borehole thermal storage was modelled using a hybrid step-response model from the IDEAS library. This model considered both short-term and long-term thermal responses between boreholes and the surrounding ground with relatively low calculation effort. The thermal response models have been validated by the model developers (Picard & Helsen, 2014).

This research used an adaptive time-step size solver Radau IIa with a tolerance of 1E-6. The time interval for outputs was one hour.

Analysis of on-site generation and demand matching by the two methods

According to the simulation results, annual heating demand for the whole district was 3.7 GWh, including 0.27 GWh for DHW. Peak heating load per area varied from 53 W/m^2 to 149 W/m^2 (67 W/m^2 in average) for different buildings, which was consistent with the corresponding design parameters.

To further investigate the influences on analysing the performance of demand, generation and thermal storage by the two modelling and simulation methods, this research generated four simulation case studies, namely Case1-M1, Case1-M2, Case2-M1 and Case2-M2. Case1 only considered short-term thermal storage together with the solar thermal system and industrial waste heat. Borehole thermal storage was added in Case2 to study the benefits in the long-term. M1 represents case studies that were simulated by a steady-state approach in EnergyPLAN. Case studies named M2 were modelled and simulated by a dynamic approach in Modelica.

Figure 5 provides the hourly heating consumption distribution throughout the year for the case with seasonal thermal energy storage using the two methods. The peak heating demand simulated by M2 was larger than the heating demand for Case2-M1. This difference was caused by the diverse of controlling methods for the heating system. As described in the previous section, the space heating consumption was calculated under perfectly controlled condition and input into EnergyPLAN as a fixed data profile. However, the heating system model for Case2-M2 applied an on/off control for the heating sources to satisfy the supply temperature was 60 ± 1 °C. It was very likely to arise the overheating phenomena thus consumed more heating energy. Apart from this, the overall heating demand distributions using the two methods were very much the same.

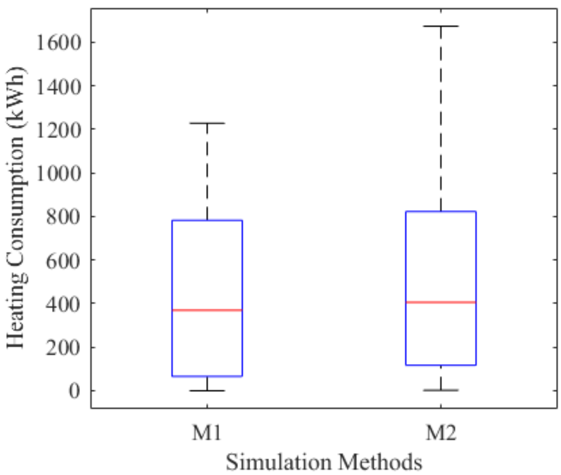

Figure 5: Hourly heating consumption distribution throughout the year for Case2-M1 and Case2-M2.

Since the focus was on analysing the amount of excess heat recovered from the copper plant and stored in the thermal storage, this study selected on-site heating energy fraction (OEF) and on-site heating energy matching (OEM) as performance indicators. OEM represents the percentage of heat generated by on-site energy used in buildings. OEF represents the percentage of heating demand covered by on-site energy. Here, in this study, on-site energy generation referred to solar thermal energy and heating stored in short-term or long-term thermal storage. Equations for calculating OEF and OEM are described as below.

$$OEF = \frac{\int_{t1}^{t2} Min[L_{SH}(t) + L_{DHW}(t); G_{solar}(t) + G_{storage}(t)]dt}{\int_{t1}^{t2} [L_{SH}(t) + L_{DHW}(t)]dt} \quad (3)$$

$$OEM = \frac{\int_{t1}^{t2} Min[L_{SH}(t) + L_{DHW}(t); G_{solar}(t) + G_{storage}(t)]dt}{\int_{t1}^{t2} [G_{solar}(t) + G_{storage}(t)]dt} \quad (4)$$

where L_{SH} is space heating load, L_{DHW} is domestic hot water consumption, G_{solar} is heating generated by the solar thermal system, $G_{storage}$ is heat stored in thermal energy storage, t is simulation time-step, which is one hour in this study.

In addition, to better understand how OEF and OEM represent the relationship between heating generation and demand, the following two extreme examples are helpful. If OEF and OEM are equal to zero, all heating demands are served by off-site heating generation and all on-site heating generation is wasted. In contrast, the optimal utilization of on-site heating generation requires that both OEF and OEM are equal to one. In this situation, all heating demand is satisfied by heating generated on-site and no more on-site heating generation is dumped into the environment.

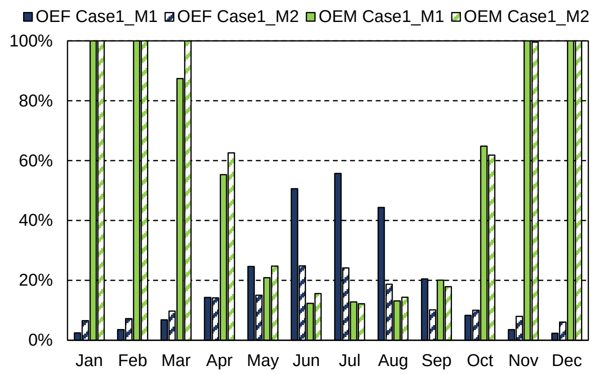

Figure 6: Monthly on-site energy fraction and on-site energy matching for Case1-M1 and Case1-M2.

As for Case1, where only short-term heating storage was taken into account, this study calculated monthly OEF and OEM through results by simulation approaches M1 and M2 for case 1, as shown in Figure 6. OEM during cold months (November to March) could reach one, therefore all heating generated from the solar thermal system with short-term thermal storage was consumed by buildings. However, OEF was simultaneously lower than 20%. More than 80% of heating demand was provided by heat recovered from industrial processes of the copper plant. During the warm months, OEF slightly increased but OEM decreases dramatically compared to the cold months. This phenomenon demonstrated that more demand could be covered by the on-site heating generation. However, heating generated by the solar thermal system was not fully used. The results implied that the current design needs a better control strategy to engage energy flexibility or a larger short-term thermal storage to shift heating load.

Comparing results generated by the two simulation approaches, M1 and M2, for Case1, the discrepancies for monthly OEM was less than 7%, except for March, which is 13%. The differences for OEF appeared much larger than for OEM, especially for the warm months when heating demands were low and solar irradiance is high. The most plausible reason for the differences was the different simulated solar thermal energy by the two simulation approaches (as shown in Figure 7). In the energy-planning approach (M1), heating generated by the solar thermal system was only affected by the distribution of solar irradiance. However, in the dynamic energy simulation method (M2), an extra control of return temperature back to solar collectors was applied to avoid evaporation inside collectors. When return temperature back to the solar collectors was higher, the heating generation from the solar thermal system was lower as a consequence.

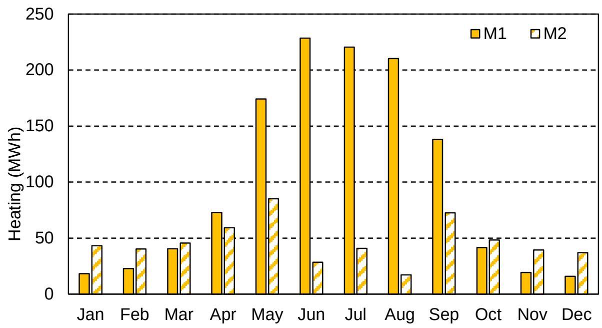

Figure 7: Monthly heating generation from solar thermal system (with short-term storage) by different simulation approaches.

Figure 8 provides a further insight of the calculated hourly heat generation of the solar thermal system including the short-term storage by the two simulation methods. Both heating generation profiles showed a direct proportion relationship with the solar irradiance but the peak hours appeared a couple of hours later due to the short-term thermal energy storage. It is worth noting that the heating provided by the solar thermal system in Case1-M1 was higher and covered more hours than in Case1-M2. In Case1-M1, the heating demand was always priory satisfied by the solar thermal system with the short-term storage despite the temperature in the whole network. However, in reality, the heat transferred from the solar thermal system to the demand side can only be accomplished when there is sufficient temperature difference between the two sides. This statement can also be supported by the results shown in Figure 7. During the warm season (from April to September) when the heating load was low and return temperature was high, the simulated heating generation from the solar thermal system by the dynamic method (M2) was lower than the one predicted by the energy planning method (M1). The cold season was vice versa. Therefore, in this case, the representation of the dynamic simulation method was closer to the real-world system.

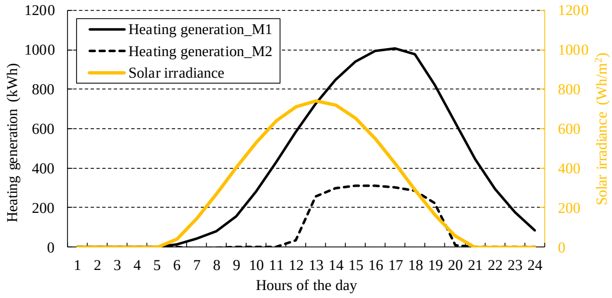

Figure 8: Hourly heat generation by the solar thermal system (with short-term storage) on a typical summer day (21st of June).

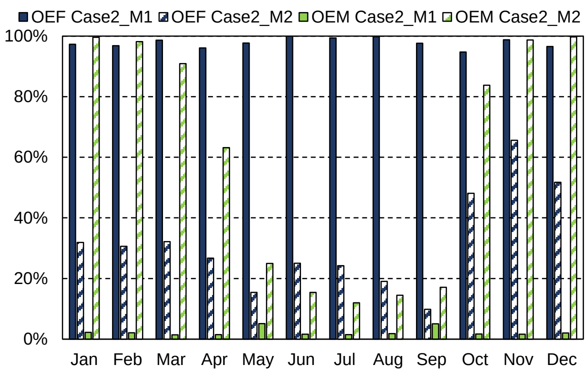

Figure 9: Monthly on-site energy fraction and on-site energy matching for Case2-M1 and Case2-M2.

Figure 9 illustrates on-site heating generation and demand matching for the case with long-term thermal storage. We observed significant differences between the two methods. For the results generated through the energy-planning method (M1), OEF always reached one throughout the whole year and OEM was less than 5%. The results implied that the on-site generation was over-satisfied for heating demand. For the results generated through the dynamic energy simulation method (M2), OEF was around 30% from January to April and more than 50% from October to December. The increasing utilization of on-site heating generation benefited from the application of long-term thermal storage. However, for the rest of the year, from May to September, OEF and OEM remained the same as in Case1. The results were reasonable since the system scheme of Case2 was the same as Case1 when the long-term storage was inactivated.

In Figure 10, it is clear to see that the thermal storage continuously increased the stored energy in the first day of simulation and was charged immediately when there was extra generated heat available. The storage energy rose from 0 to 5.3 MWh in one hour. In addition, it is apparent from the figure that the amount of the stored energy was much larger than the heating demand (space heating and DHW). This phenomenon supported the findings of the OEF for Case 2-M1 always reached 1 and OEM was relatively small as presented in Figure 9.

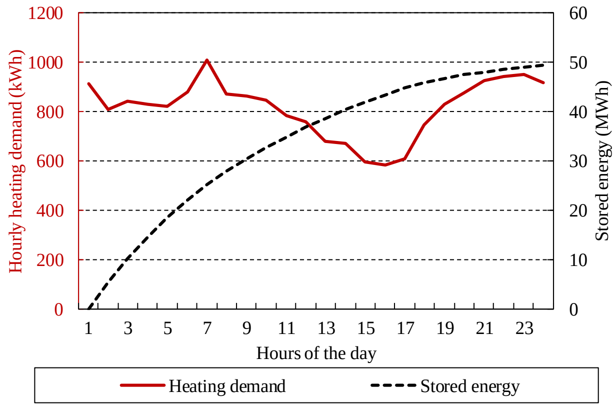

Figure 10: Hourly storage energy in the long-term thermal storage and heating demand for Case2-M1 on 1st of January.

Discussion

As mentioned in the literature review, a large variety of models are available nowadays, thanks to the great efforts devoted by previous researchers along several decades. According to the authors' experience, it sometimes happened that the interpretations from the real-world systems to the simulated models were not explained explicitly in some modelling and simulation tools, especially when applied to new technologies or concepts. The new technologies or concepts may have different application conditions that currently available modelling methods have not taken into account. This would be a challenge for applying available modelling and simulation methods to the new generation district heating system. Therefore, the authors would like to get a better understanding of under which condition(s) a method can or cannot be applied to certain cases through this research. The research has presented the results of a comparison of two simulation methods for analysing the performance of a district heating system utilising waste heat, solar energy, and thermal storage. One important finding is that both methods generated similar results regarding OEF and OEM for the case with only short-term thermal energy storage. The model built by the energy-planning method was more idealized with fewer constraints. It could be a representation of a perfectly controlled system which may never be realized in reality. The simulation conducted by the energy-planning method in EnergyPLAN was superior in computational time. The model run time of a year simulation was in the order of seconds. While for the dynamic simulation in Modelica, the simulation time for a year was in the order of hours in this research. Noted that model run time for the dynamic simulation methods may vary when choosing different solvers, tolerance levels, time step sizes and computational performance of processors.

Another finding from this research was that the application of the long-term thermal energy storage did contribute in improving the utilisation of the industrial waste heat. However, the results of this research also show significant discrepancy between the monthly on-site energy fraction and on-site energy matching produced by the two simulation methods. The charging and discharging process of the long-term thermal storage was on hourly basis which supposed to be much longer in reality. The storage medium has to be heated up to a certain temperature level in order to be extracted (Sibbitt et al., 2012). The dynamics of the heat should be analysed to get information on the time periods as well as the temperature levels of charging and discharging (Reuss, 2015). Taken together, the results indicate that the energy planning method used in this study showed limitations in analysing the performance of a district heating system with long-term thermal storage.

Apart from the current application in the presented system configuration, the results and suggestions could also be extrapolated to other projects with solar energy systems and thermal storage charged by different heating sources at similar temperature level. As long as the other heating sources could provide a constant input or be regulated constantly.

Conclusion

This research set out to investigate the effect on energy balance by different modelling approaches for a new generation district heating system using industrial waste heat and solar thermal energy with the aid of short-term and long-term thermal storage systems. The analyses were conducted through two different simulation approaches, a simple energy-planning method and a dynamic energy simulation method. The results revealed that the both methods were sufficient to analyse the performance of new generation district heating systems using solar thermal energy and another low-temperature energy source without long-term thermal energy storage. An advantage of the energy planning tool was that simulation time was second-based, therefore making it suitable for projects in the feasibility study phase. However, the energy planning method should not be applied if long-term underground thermal energy storage is included, due to the fact that the charging and discharging process was modelled on hourly basis in EnergyPLAN.

Efforts for both model preparation and simulation execution were much higher than energy-planning methods, which limited the possible applications in the feasibility study phase.

The second goal of this research was to analyse the technical feasibility of the investigated system. The results of the research indicate that heat generated by the solar thermal system including the short-term thermal storage was not fully used during the warm months while extra heating from the industrial heat recovery system was still required. The long-term thermal contributed in improving the utilisation of the industrial waste heat.

To conclude, the present study explored the viability and limitations of the two simulation methods. In order to overcome the limitations, our future research will focus on identifying sensitivities of parameters and simplifying less sensitive parameters for dynamic simulation approaches. Uncertainty analysis will also be conducted in future work for a better understanding of risk assessment when simplifying models.

Acknowledgements

This research is part of the seasonal storage for solar and industrial waste heat utilisation for urban district heating project funded by the Joint Scientific Thematic Research Programme (JSTP) – Smart Energy in Smart Cities. We gratefully acknowledge the financial support from the Netherlands Organisation for Scientific Research (NWO). We would also like to thank our research partners from Tsinghua University with the project of the International S&T Cooperation Program of China (ISTCP) (project No. 2015DFG62410). Without their efforts, we would not obtain the technical data to conduct the case study.

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