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Modelling of District Heating Grid

Master's thesis in MSc Sustainable Energy Systems

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Abstract

Keywords: Modelling, District heating, Network, Thermal behaviour, Hydraulic behaviour, Optimization, Flexibility, Python.

The modelling of the district heating grid is of a great significance to the district heating owners and shareholders; simplifying the distribution network through simulation modelling offers a possibility of analyzing its performance, forecasting its behavior and, accordingly, adding an important piece to optimize the generation of heat and explore the potential of utilizing the grid performance for flexibility provision. This work aims to develop a simple, comprehensive, and open-source tool that can capture the behaviour of the district heating networks

To achieve the modelling objective, the research strategy identified a set of KPI's to qualify a suitable modelling approach. A modelling algorithm was then developed to set the modelling steps and identify the required checkpoints. Furthermore, a simplified model was constructed to facilitate the mathematical modelling (the physical relation between parameters), and then a computer code was developed using Python programing language with Anaconda environment. This thesis adopted two modelling procedures: The grid as a storage model and the delay analysis model.

The models generated the following parameters: the customer supply temperature and the grid volume flowrate are calculated to illustrate how the generation units are operated to meet the customers' heating demand. Furthermore, heat loss is estimated as it's an essential parameter to the feasibility of district heating systems. And finally, the generation return temperature is a crucial indicator of the customers' efficiency in utilizing the supplied heat and affects the efficiency of the generation unit. The above parameters were compared to the generated data of grid performance, and the two models yielded relevant results that followed the trend of the actual grid performance.

The models' ability to provide insights into the grid performance is investigated. The two models presented the grid performance with the possibility to use them for optimization. They also indicate the potential of using the grid as heat storage to provide flexibility.

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Mohamed Awad, Gothenburg, May 2022

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1. Introduction

This chapter presents some background information regarding the topic before describing the problem. Furthermore, the chapter explains the aim and objectives of the research.

1.1 Background

Humanity faces one of the most threatening challenges of all time, climate change. Inter-Governmental Panel's recent report on Climate Change indicates that human activities contributed to and still have the potential to determine the future of our climate (IPCC, 2022). Furthermore, the same report states that carbon dioxide is the primary driver of climate change, although other greenhouse gases and pollutants also affect the climate.

The Global Energy Outlook indicates that heating is the largest end-use energy as it accounts for around half of the energy used today, more than electricity (20%) and transport (30%) (International Energy Agency, 2021). The international heating market relies heavily on fossil fuel sources, with coal, natural gas, and oil meeting more than 75% of the global heating demand. Therefore, the heating sector accounts for more than 40% of energy-related carbon dioxide emissions in 2018 (International Energy Agency, 2021), and this share has remained constant for the past decade. Therefore, the decarbonisation endeavour must decouple the provision of heating services from the exploitation of fossil fuel resources and increase the efficiency of the heating systems (IPCC, 2022). The 2050 net-zero scenario indicates that the share of heat pumps, low carbon district heating and renewable-based heating will exceed 80% of sales in 2030 (International Energy Agency, 2021).

District heating (DH) is a well-established energy technology, especially in Nordic countries, Eastern Europe, Russia, and China. It offers more efficient space heating and hot water provision to residential and service sectors in terms of energy and cost compared to conventional/decentralised generation methods(Wiltshire, 2015). Moreover, as the global concern of climate change emerges, the district heating systems are preserved to have a significant role in the energy transition due to:

1. Sustainability of generation: the district heat is usually generated from various resources and generation technologies. However, renewable energy resources like biomass are the market leader in countries like Sweden and Denmark. In 2019 Sweden generated 63% of the district heating from biomass, equivalent to 37.8 TWh (SEA, 2022). On the other hand, the aggregated generation from coal, natural gas and petroleum products accounted for only 6%. Moreover, combined heat and power plants (CHP) utilise biomass and waste to produce electricity and heat. CHP plants, by principle, increase the energy utilisation factor (EUF) and leads to better use of available fuel energy (Kharchenko & Kharchenko, 2014). The process of incinerating municipality solid wastes (MSW) is used as a heat source for heat generation as well as cogeneration plants where electricity and hot water are supplied.

2. Interlinkage with the electricity sector: Consumption of district heating for space heating and hot water relieves some pressure from the electricity suppliers and enhances energy efficiency over the spectrum of primary fuel and energy services, compared to when consumers use electric boiler/ tank to fulfil their demand (Frederiksen & Werner, 2013a). It might be an intuitive conclusion that DH might lead to a lower price of electricity, but then it must be mentioned that in 2019 Sweden generated 7% of the DH using heat pumps which utilise electricity to provide hot water. Furthermore, the DH system could be used to provide flexibility to the electric sector by means of operation optimisation and cost efficiency, i.e., thermal energy storage (TES) could be used for peaks shaving and therefore reducing the need for dispatchable fossil fuel units and decouple the electricity and heat generation in the CHP leading to the more flexible use of these power plants(Frederiksen & Werner, 2013a).

3. Inclusion of renewable energy sources: the higher penetration of renewable energy sources (RES), the more strategies are needed to manage the variability of these sources. TES coupled to DH network, and generation units can provide such flexibility, i.e., CHP could be shut down when the electricity prices are low for long durations utilising TES for heat supply and enhancing the feasibility of RES. Furthermore, the heat pumps can minimise the RES energy curtailment, i.e., during the events of high heating demand and high wind generation. (Göransson et al., 2020).

Sweden started a district heating operation in the early 20th century and expanded in the second half, and the current production exceeds 56 TWh (SEA, 2022). The below figure illustrates the generation mix in 2019. Gothenburg is considered a world leader in the field of DH. Currently, more than 17,000 city buildings, approximately 90% of the city buildings, are connected to the DH grid (CTCN, 2022).

1.2 Problem description:

The problem that this thesis addresses is the lack of digital representation of the district heating network. The properties of a DH network with connected buildings to a generation unit give opportunities to optimise the operation concerning costs and operate flexibly. Nevertheless, the problem here is how to represent those properties.

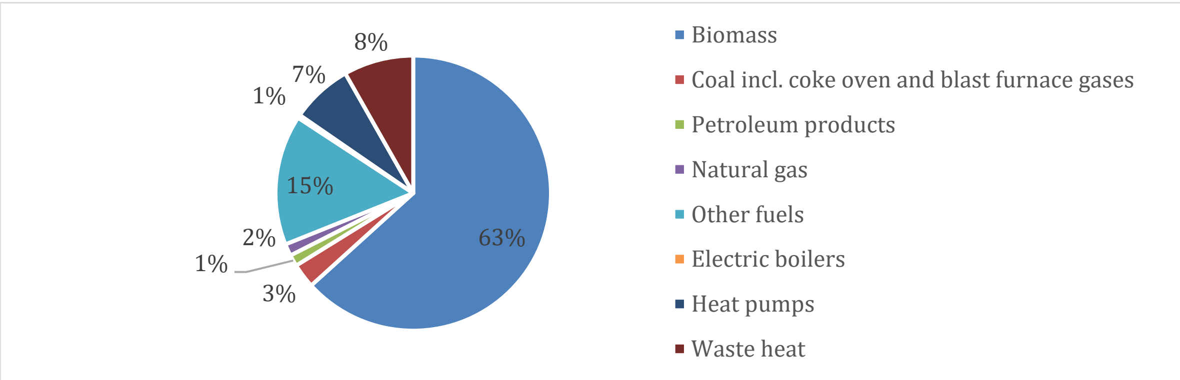

Figure 1 District Heating Generation in Sweden 2019

1.3 Research's aim and objectives:

The purpose of the district heating grid's model is to simulate the rate of the energy transfer through the grid (Arce et al., 2015). This project aims to utilise the heating production and consumption data to investigate the current district heating grid by developing a simple, representative, and open-source model than can capture the grid behaviour complexity and provide some insights to the DH companies. Moreover, with reliable accuracy, the model should be able to capture the behaviour of any district heating network. The behaviour could be simply identified as the thermal and hydraulic characteristics of the grid performance.

The following research questions were formulated to support delivering the above objectives:

RQ1: What are the desired features of the DH model? What modelling approach is to be used to develop such a model?

The purpose of the model is to build a digital representation of the reality; that aims to capture the behaviour of the physical grid. It is also crucial to clearly identify the desired features of this model, perform an informed trade-off, and illustrate the model's capability to meet its objectives. It is worth noting that the model is not the reality. However, having reality as a reference to calibrate the model output can enhance the accuracy of the modelling work.

RQ2: What are the thermal/ hydraulic characteristics of the district heating network according to the developed model, and how do they perform compared to the actual grid?

This question shall be addressed upon completing the modelling work, and the district heating digital representation shall be fed with actual production and consumption data. The thermal and hydraulic parameters of the district heating grid shall then be quantified and assessed. Various variables shall be considered, i.e., the pattern of production/ consumption, grid geometry, soil characteristics and weather fluctuation.

RQ3: What is the potential application of the district heating model?

This question illustrates the potential, challenges, and benefits of using the developed grid model to optimise the grid operation and evaluate the available grid flexibility. It will also address the impact of such use on the current grid infrastructure and components.

This master thesis provides the following preliminary deliverables: A prototype of a model that can capture the behaviour of DH grids. The results of the model in providing grid insights. An analysis of the obtained results.

2. Literature review

This chapter describes the concept of district heating from both a customer perspective and a system perspective. Afterwards, the characteristics of district hearing system are presented and explained. Lastly, the different models used in DH network modelling are described and contrasted against one another.

2.1 The concept of district heating:

The basic concept of district heating (DH) is to satisfy local demand for heating service by delivering the heating load from a local source of energy through a network of pipes (Frederiksen & Werner, 2013a). An essential prerequisite of the DH system is to illustrate significant cost competitiveness compared to heating at the service location, whether it's residential, commercial or industrial, via boilers or direct electric heating (Wiltshire, 2015). The local factor is significant to justify such a system; the heat generation must be done locally using an available cheap fuel. The energy supply can come from a secondary source, a primary renewable source, or a primary fossil source. Moreover, a local marketplace of customers is obligatory for forming a DH system to minimise distribution losses and capital investment. The supply of energy is delivered to the customers through a piping grid, the modern DH system consists of a supply pipe delivering a hot fluid, most commonly water, but some systems use low-pressure steam as an energy carrier to the customer's substation where the heat can be used for space heat, domestic use, commercial use, and in some cases to meet an industrial low-temperature demand (Wiltshire, 2015).

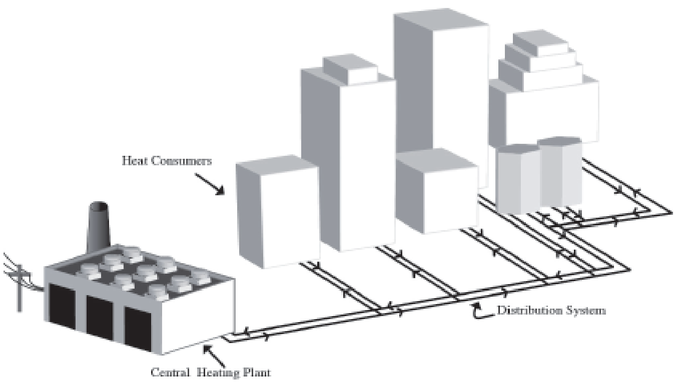

Figure 2 Basic concept of district heating (Phetteplace et al., 2013)

From a customer perspective, being connected to a district heating system has a variety of benefits; the DH provides a modern and reliable heat delivery as it usually utilises an available fossil-free fuel with no significant investment by the customer, i.e., the required payment would be related to the optimally designed substation at his location with no oversizing compared to the heating boiler. The DH requires less space at the customer's end and reduces the risk of fire and explosion as it eliminates the usage of fuel combustion in the buildings (Frederiksen & Werner, 2013a). On the other hand, several drawbacks have also been discussed from the customer perspective: individuals will have a low bargaining power to negotiate system price and delivery costs. The switching cost to an alternative heating system would be high in the same context. In addition to that, the system's failure will affect a high volume of customers (Frederiksen & Werner, 2013a).

From a system perspective, the following characteristics of district heating are usually discussed: one of the primary justification of DH systems is the economy of scope; it's cheaper to jointly produce similar goods rather than producing them separately. Another related aspect is the economy of size, which was a major driving force throughout the history of DH; the concept suggests it's cheaper to produce at higher product volume, this implies a higher efficiency of the generation unit, better environmental protection, and lower specific generation cost (Kharchenko & Kharchenko, 2014). The flexibility of the DH is another crucial aspect referring to the ability to change the merit order of the generating units when market condition changes. The environmental impact at the local level is lower when for DH compared to the locally combusted fuels (except in the case of CHP). Finally, the security of supply is higher for the DH compared to the local combustion; this advantage is created by the local replacement of fossil fuel, the higher degree of recycling heat and the more prominent inclusion of renewables in the DH systems. These same reasons support the claim of lower environmental impact from Carbon dioxide emission in the DH systems (Frederiksen & Werner, 2013a).

2.2 Characteristics of district heating system

Modern district heating systems, supplying heat to either big cities or small towns, have some essential components, i.e., a heat source, a heat distribution network, a customer/ network connection, and a connected customer (building) (Wiltshire et al., 2016). The conventional DH system supplies water at high temperatures (high-temperature district heating HTDH). HTDH delivers water at a temperature range of 70 ^{o}C to 120 ^{o}C and has a return temperature between 45 ^{o}C to 65 ^{o}C (Thalmann et al., 2018). In HTDH, heat generation is centralised; the production units are usually CHP, industry heat excess, and heat boilers, while storage tanks are used for peak handling. Coal, natural gas, oil and waste are used as a generation fuel in HTDH systems (UCL, 2017). The modelling work of this thesis shall focus on the HTDH networks, with heat loss assessment usually being referred to as a key performance indicator, and it usually falls in a range of 7% to 22% in densely populated locations (Brocklebank et al., 2018).

A state of art district heating design emerges as a response to the demand for higher system efficiency and more renewable energy resources. It has a supply temperature of 45 ^{o}C to 55 ^{o}C and a return temperature of 15 ^{o}C to 25 ^{o}C. Provisions of long-term thermal storage and a coupling of the electricity and heat supply were introduced to increase efficiency and optimise the DH system (Kallert et al., 2021). LTDH aims to balance the quality of the supplied energy as it maximises the use of low-temperature supply and reduces distribution losses by minimising the temperature levels in the grid (Brocklebank et al., 2018). LTDH avoids fossil fuel usage; therefore, solar, geothermal, and heat pumps are the leading technologies of this system. The distribution losses of this system fall between 5% to 10% (Brocklebank et al., 2018).

An emerging concept is the 5th generation of district heating, also known as ambient temperature district heating (ATDH) (Gudmundsson et al., 2021). The 5th generation system temperature is insufficient to meet the connected customer heat demand. Therefore heat pumps shall be installed at the customer's end to elevate the temperature to the desired levels (Gudmundsson et al., 2021).

Heat source: As explained previously, low cost per unit of heat produced and low environmental impact on a local level are the main characteristics of DH sources. It is worth noting that fossil fuels like coal, natural gas and petroleum products are still used for DH generation. Generation units connected to large cities are typically thermal power plants, where steam is usually extracted are multiple points to heat the DH water (Wiltshire et al., 2016). In many locations, the DH is supplied with energy from waste incineration plants. Therefore, the DH units are located close to the city to avoid the cost of waste transportation and the losses associated with long distances heat transfer (Wiltshire et al., 2016). It is also common to utilise the low-grade heat of flue gas to generate district heat; such a method could be found in economisers used with gas-fired combined cycle gas turbine (CCGT) and CHP plants.

Heat distribution: the primary purpose of the district heating network is to deliver heat to the customers and return the hot water to the generation unit. The system, therefore, consists of supply and return pipes either installed above-ground or underground. The pipes could be either flexible or inflexible; the material of construction is usually steel or plastic (generally in the form of high-density polyethylene HDPE), where flexible pipes are easier to install around obstacles, and it is typically used for small diameters applications that include individual buildings connections (Wiltshire et al., 2016). To avoid heat losses and prevent external corrosion of the piping system, high-quality insulation is applied, usually in the form of polyethylene foam. Means of fault detection are traditionally part of the system installation; pressure drop and leak detectors are some of the critical measurements to the distribution network.

Many factors influence the choice of DH grid's structure; it usually starts with estimating the demand's capacity, and then legal and architectural criteria are to be followed. Furthermore, regional layout, technical, geological and technical aspects are significant to the structure decision (Thalmann et al., 2018). The heat distribution grid can be classified into two main types: Tree (star) and mesh networks (Thalmann, et al., 2018). The tree type of DH is designed with the supply and return pipes are symmetrical; the pipe's diameter descends away from the generation unit and toward the customer. The heat carrier is usually water, and the system's pumps are designed to ensure that the agreed differential pressure will be available at the last customer (Thalmann, et al., 2018). The tree structure is relatively more straightforward to construct due to the short pipe lengths and small diameter; these two characteristics usually lead to relatively low initial cost (Thalmann, et al., 2018). However, the disadvantages of the tree structure are the hydraulic difficulty of expanding the grid without shutting it down and compromising all customers' supply. The simplest form of the tree structure is the line network, where there's one main header connected to short pipes delivering heat to customers.

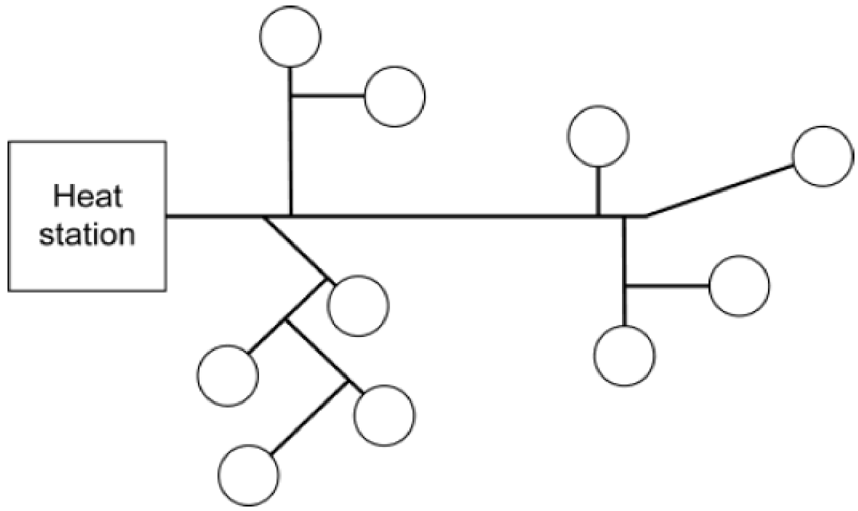

Figure 3 Tree-structured DH network (Thalmann et al., 2018)

On the other hand, the mesh networks are suitable for expanding networks and for locations with high customers density. Mesh structure usually has various supply routes with multiple heat sources and several heat centres operated in interconnected mode (Thalmann, et al., 2018). Ring-type is a particular form of the mesh network where the supply system consists of one pipe supplying heat directly to the house's connection pipe (Thalmann, et al., 2018).

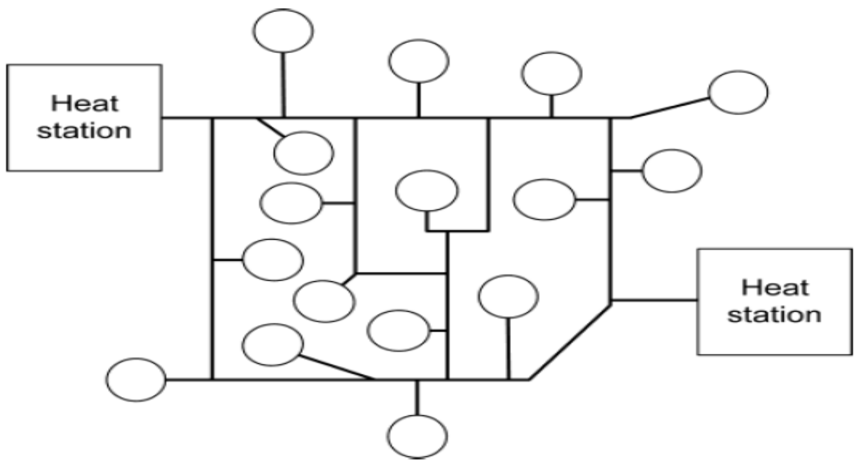

Figure 4 Mesh structured DH network (Thalmann, et al., 2018)

Customer's interface: The customer may be connected to the distribution grid either directly or indirectly. Direct connection is quite simple. However, it requires the heating circuit in the building to handle the distribution pressure; such an arrangement usually leads to lower return temperature, lower space requirement and lower maintenance costs (Wiltshire et al., 2016). On the other hand, handling the distribution pressure implies a relatively high initial cost. An indirect customer interface is achieved via a heat exchanger (HX) to decouple the network and the customer pressure. The local controls available at the interface point are designed to limit the building s intake and ensure the flow balance during peak occasions (Wiltshire et al., 2016). Moreover, in the indirect interface, a crucial function of the DH local control is to reduce heat losses and pumping energy (Wiltshire et al., 2016).

Connected Customer: all customers shall have a heating system compatible with the DH system, whose owner is usually responsible for ensuring this compatibility. The heating system is designed to meet the peak demand without oversizing; it's designed to operate under varying volume flowrate and is required to ensure low-level return temperature is achieved under different conditions. An indirect heating coil with storage is usually avoided as it's pretty challenging to achieve a low return temperature with such a system's configuration (Thalmann, et al., 2018).

2.3 DH network modelling

Modelling the district heating grid is a crucial research area due to the vital role of the DH in society; it is, therefore, studied extensively. Energy systems' models can be built for a specific purpose, as illustrated by (Farzaneh, 2019), reflecting the details to be addressed by the model, such as; energy consumption and generation trends. This purpose specification is considered in many models (Farzaneh, 2019):

Demand-side models: focus on determining the final energy consumption in the entire society or particular sector as the residential buildings (Farzaneh, 2019).

Supply-side models: focus on generation technologies, usually characterised as estimating the supply-side parameters related to the technology design and, in some cases, operation parameters (Farzaneh, 2019)

Integrated models: analyse the complete set of processes within an energy system. Simulation models are widely used for this purpose as it assesses the reliability of energy generation and supply networks within the energy system (Farzaneh, 2019). The simulation model aims to build a realistic representation that provides information about the possible behaviour of the existing system. It is usually used to measure and calculate the system's performance to improve it or give details on potential failures (Farzaneh, 2019).

The modelling work varies based on the desired objective, level of details, defined boundaries, and areas of interest. A system-level/economic approach is usually adopted in earlier phases to assess the economic potential and sustainability aspects of DH. Municipalities typically perform this type of modelling work during the planning phase of Urban expansion. The properties of a DH network, with connected buildings to a generation unit, give opportunities to optimise the process concerning costs and flexible operation. The grid modelling with the objective of DH optimisation is a popular research area due to its importance to the DH owners and generation units. A recent trend in DH modelling aims to identify the heating sector's potential flexibility by using the grid as storage.

But the problem here is how to represent those properties. The modelling of the district heating network should consider two fundamental dynamics; temperature dynamics, which change in a relatively slow manner, taking a couple of hours in some cases, and the flow, which transfers at a time pace of seconds (Frederiksen & Werner, 2013).

A representing thermal model is generally developed based on transient flow conditions to simulate the thermal behaviour of the DH grid; in other cases, the analysis only considers steady-state flow parameters. The dynamic modelling approach of the district heating either considers both the temperature and flowrate to be dynamically simulated or only the temperature behaviour. Heat transfer is regarded as a dynamic behaviour when the second approach is applied. The modelling work starts with the finite element analysis, where a single energy balance is performed to estimate the heat transfer on a different axis. Another approach in dynamic modelling is the simplification of the grid's physical structure. This approach aims to reduce the computational intensity through node analysis (Brocklebank et al., 2018) and the aggregation method proposed by (Larsen et al., 2002).

The Stochastic critical point model was introduced as a simple way to capture the performance of the grid (Bøhm, 2002); this modelling approach aims to identify a several representative critical points in the district heating grid when the supply of temperature is fulfilled at these points the model suggests that the heating load in the whole grid is met (Bøhm, 2002). This modelling approach is relatively easier to implement (in comparison with other approaches) in terms of computational complexity; it, however, requires extensive accuracy assessment when addressing a complicated mesh structured network. Moreover, the critical point method isn't a good fit when the modelling objective is capturing the overall behaviour of the DH grid to a sure accuracy. Another technique is developing an equivalent network model through aggregating the network components to a single pipe; this method works for the tree-structured district heating grids, and it has two underlying assumptions: All mass flows are assumed to vary proportionally, and the return temperatures on the primary side of all heat exchangers are equal (Larsen et al., 2002). These assumptions were usually unfulfilled in practice. Moreover, the model is computationally intensive and thoroughly understands the grid geometry. However, the results of this model were found to be close to the original network (Larsen et al., 2002). This model is classified as computationally moderate; it, however, can't be applied to a mesh-structured network. In addition to that, to build an equivalent network, a complete package of the original network geometry and operation parameters should be available. A third modelling method is a combination of critical point and comparable network model; this method aims to identify the essential issues to guarantee that the heating demand is met; in addition to that, it estimates the heat losses, the pumping power consumption and the capacity of heat storage (Bøhm, 2002). The models' results were found to represent the actual grid; however, it requires a lot of computation work and a complete understanding of the grid geometry. Almost all previous modelling work that focuses on the district heating optimisation as their objective utilised an aggregation method to simplify the geometry of the grid while preserving the grid characteristics. Out of these models, two approaches were proved to give good results and therefore used extensively in later research, the first was developed by (Larsen et al., 2002) at the Technical University of Denmark (DTU), and the second was developed by (Loewen et al., 2001) at Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT). Both models aimed to reduce the tree structure of the district heating model into a line structure and remove short branches in the grid. The German method had a model to simplify the grid loops. The two methods were compared using Shoes grid in Denmark as a case study. The Danish process reduced 44 pipes to 3, while the German aggregated 44 pipes into ten without significantly increasing the errors (Larsen et al., 2004).

Currently there are couple of available simulation tools with different objectives and underlying assumptions. THERMOS is a tool developed to enable municipalities to assess the economics and potential of district heating without technical details (Vorspel & Bücker, 2021). Therefore, it doesn’t address the level of points required to capture the behaviour of the grid. DHNx is another tool used to optimise the routing and dimensioning of the district heating grid and hydraulic and thermal simulation (Vorspel & Bücker, 2021); it’s thus used for planning purposes. TESPy, on the other hand, is a python tool used to design thermal plants and simulate district heating networks; it’s built in a modular structure with three main modules: network, components, and connections (Witte & Tuschy, 2020). DiGriPy is an open-source tool; that was recently developed to simulate the grid based on the heat demand time series of the connected building and the grid’s pipe geometry and insulation (Vorspel & Bücker, 2021). It identifies the required heating by solving the pressure, temperature, and velocity along the pipe for each timestep (Vorspel & Bücker, 2021).

3. Methodology

The methodology chapter describes the developed modelling's key performance indexes (KPIs), and then introduces the modelling algorithm adopted by this project. Furthermore, this chapter demonstrates the details of the DH theoretical models and presents the mathematical expression utilized in the modelling work.

3.1 Research Strategy

The thesis studied the available modelling work in the literature along with the available modelling work at Utilifeed AB company. To align the modelling objectives with the chosen methodology, this research identifies key KPIs to qualify suitable modelling approaches. A modelling algorithm was then generated based on the energy systems' modelling guideline presented by (Farzaneh, 2019). The algorithm specifies the set of activities that's followed in this thesis work and also identifies a reference check points. A simplified model was then developed to avoid the complexity of the actual grid and facilitate the construction of the mathematical model. This thesis work identified two suitable modelling approaches and implemented them following the illustrated algorithm. The modelling work was then evaluated against the actual grid parameters and the grid insights were then presented.

3.2 Data Collection

The data for the modelling work is provided by Utilifeed AB company, the modelling work was initially tested with dummy data to test the steady state convergence for each model. The model was then fed with a generated data, from 2019, and the dynamic behaviour of the grid was then modelled. The 2019 data, also provided by Utilifeed AB, covers the supply and return temperature, volume flowrate, heat generation and demand measured on a hourly basis. The data was aggregated for both generation and demand, therefore the modelling work focuses on the overall grid performance and insights rather than individual substations. The feed data is a processed data which underwent a sanity check it has therefore a limited numbers of events with unusual range of parameters. Both models have a certain set of parameters as input for dynamic simulation: generation supply temperature, customer return temperature, and demand side energy. The obtained grid parameters were then evaluated against the actual values which were part of the received data as well, mainly the customers' supply temperature and the generation return temperature and the grid's volume flowrate. The heat loss identified by the model is benchmarked against data from the literature due to unavailability of accurate losses estimation in the provided dataset.

3.3 Modelling KPIs

The objective of this master thesis is to develop a model that captures the behaviour of the DH network; it also has a primary deliverable of developing a prototype tool based on that model and providing insights of the DH grid based on the developed model. When developing a model, the first step is to identify a clear description of the model's features; the following key performance indexes were created for this purpose:

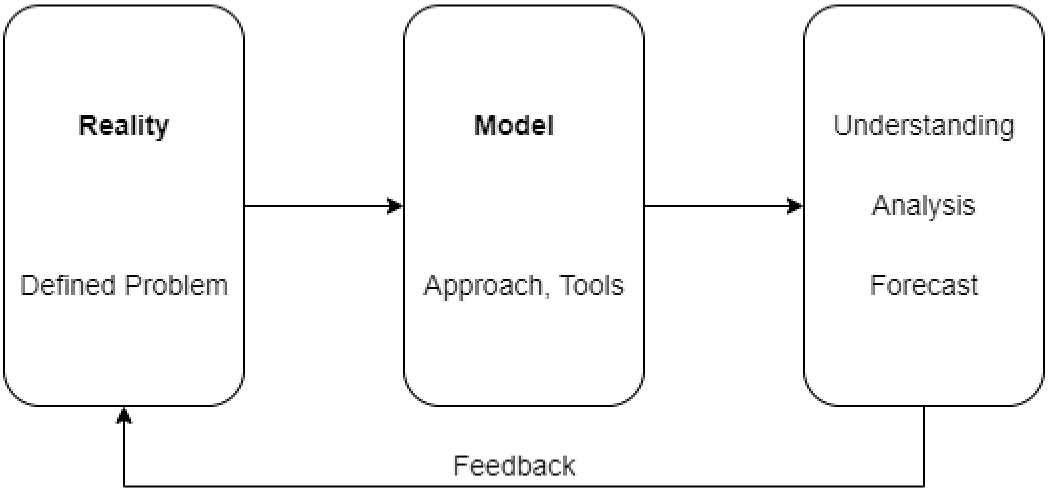

Figure 5 Model Structure

Accuracy: As illustrated in the previous chapter, modelling work can either focus on thermal and hydraulic performance and therefore simulate them simultaneously or focus only on thermal behaviour. In both cases, the model's performance to capture thermal behaviour (supply and return temperatures, energy losses) and the hydraulic performance (flowrate in supply and return pipes) shall be benchmarked against reality. The model isn't a reality; however, it should be able to transform the complexity of the reality into a simpler but representative form that is more suitable to comprehend and analyse (Unger et al., 2010). Thus, the model output shall benchmark against the actual performance of the grid to determine its reliability. One characteristic of an accurate model is that it follows the trend of reality. Another indicator is the absence of persistent error that follows a specific pattern.

Intuition and ease of use: Most of the explored DH models deliver reliable results under precisely defined conditions and simplify the complexity of the actual grid. However, that is usually associated with computational complexity, especially in the case of dynamic modelling of both thermal and hydraulic behaviour. One commonly used method is reducing the physical structure to a simple representing form; such a method fits small DH networks well; however, it is harder to apply to a complicated system. It is possible to do the network reduction work with some software, but the setup work is still time-consuming. One of the model's desired characteristics is the ease of initiation and operation, where minimum work is required beforehand. The modelling structure, either based on physical relations or empirical equations, should be easy to grasp and follow. Moreover, handling different parameters and adjusting model conditions should be intuitive to the average model user.

Robustness and resilience: A model is called robust when its accuracy and performance don't change significantly under different conditions. On the other hand, the model's resilience refers to its capacity to deal with change. The modelling work will be based on real-time operation data that could, in many cases, experience a sharp increase or decrease, a fluctuation, or in some extreme situations, faulty readings reflected in a sudden or persistent change of the data trend. In addition to that, The DH sector undergoes remarkable changes every calendar year in terms of heat supply and consumption, outdoor and ground temperatures, and, subsequently, operation strategy and heat losses. Therefore, the model's ability to preserve a certain level of accuracy is a crucial indicator in assessing the model's performance. Therefore, a model is required to work effectively and produce acceptable results regardless of the turbulence of feed data.

Data Intensity: The thesis work aims to develop a model that can make use of the available data to deliver results of reasonable accuracy. There's a variety of data requisition depending on the modelling approach. For example, for a simulation model, production/ consumption data and weather profile facilitate the comprehensive analysis of every system. On the other hand, forecasting models rely on historical data for trend analysis and therefore deliver an accurate forecast for a specific duration. Achieving the aim of the models requires extensive testing to evaluate the model accuracy with different detail levels and observe the outcome at each stage. In some cases, the more detailed the model, the more accurate results are generated as more features are likely to be applied with data availability (Downey, 2017). However, it is quite often that simple models are adopted to analyse complex systems as they're easier to work with, and they provide insights that are clear and more persuasive (Downey, 2017).

3.4 Modelling approach

An algorithm was developed to cover the modelling scope based on previous work (Farzaneh, 2019). The modelling approach was chosen based on the thesis scope of work, capturing the behaviour of the district heating network; such a scope of work falls within the boundaries of simulation modelling (Farzaneh, 2019). Both thermal and hydraulic behaviour shall be reflected in this model. It is assumed that a feedback loop can be created between these parameters to validate the modelling outcome. The modelling work shall start with a steady-state simulation, and then modelling shall be extended to cover the dynamic behaviour of the grid.

Two models were developed based on the algorithm illustrated in figure.1 and the described modelling approach. The first model analysed the delay behaviour to reflect the thermal behaviour of the grid. In contrast, the second model aimed to simplify the grid and determine its thermal and hydraulic characteristics.

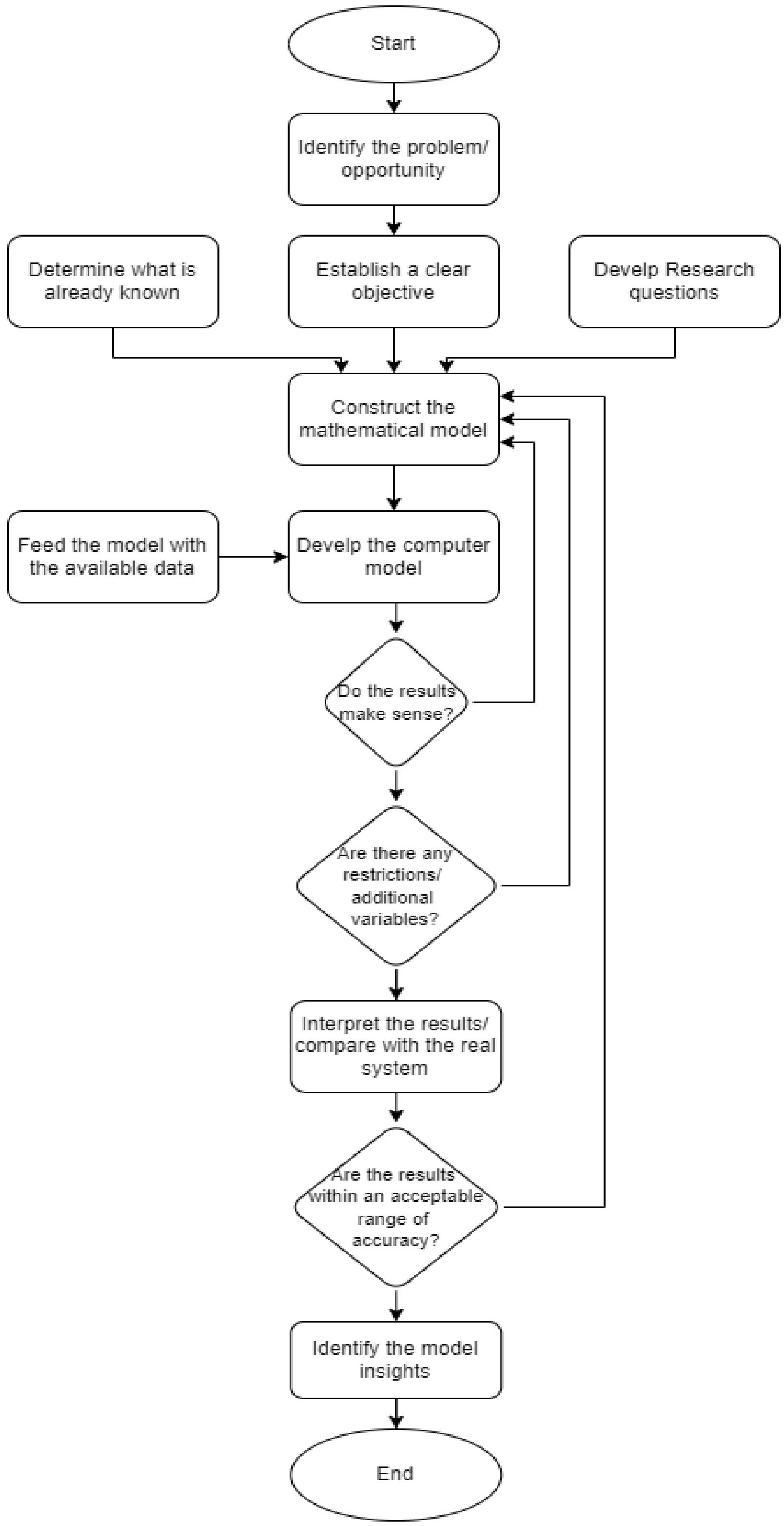

Figure 6 Modelling algorithm

3.4.1 Delay Analysis Model

This model is based on a previous work presented in (Wang et al., 2017) and (Stevanovic et al., 2009), where the thermal performance was analysed. Two-dimension heat transfer analysis was done on a finite element to estimate the thermal characteristics, including landing temperatures: customer supply and generation return temperatures and heat losses (Wang et al., 2017). In this thesis, this approach was extended to reflect the behaviour of a couple of hundreds of hours. The delay parameters were calculated for a short duration and then generalized for an extended period to test the resilience of the method. The model takes advantage of a simplified form of the network to estimate the hydraulic parameters of the grid. The following steps are applied on both supply and return pipes:

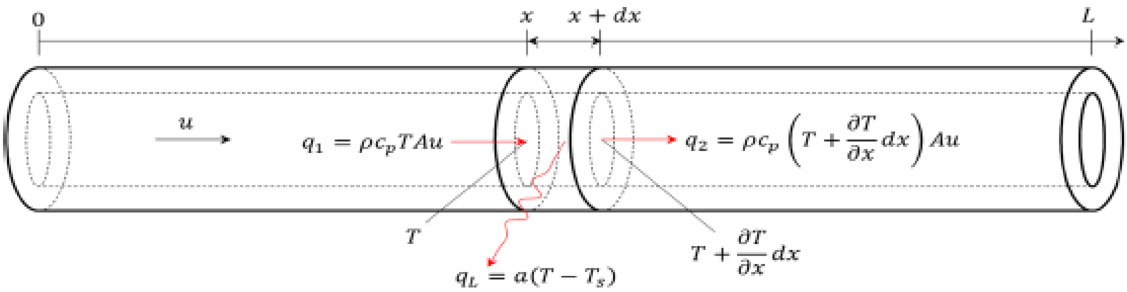

Figure 7 Heat Transfer in the district heating system pipeline (Wang et al., 2017)

Performing an energy balance around the segment x:

$$q_1 - q_2 = q_L \tag{1}$$

Where $q_1$is the heat entering the segment x, q_2 is the heat leaving to the next pipeline segment and q_L is heat loss to the ground.

$$q_1 = \rho \, C_p T \, U \, A \tag{2}$$

$$q_2 = \rho \, C_p (T + \frac{\partial T}{\partial x}) U \, A \tag{3}$$

$$q_L = \alpha \, (T - T_o) \, dx \tag{4}$$

Where ρ is the water density in Kg/m^3, C_p is the specific heat capacity of water in KJ/ Kg. C, T is the temperature in C, A is the heat transfer area in m^2, and U is the heat transfer coefficient in W/ (m^2.C). T_o is the soil temperature in C that can be determined with empirical function based on the outdoor temperature (Kreider, 2019) and α is the rate of heat loss per unit length pipeline. Combining the above equations:

$$\rho\, C_p \frac{\partial T}{\partial x}\, A\, dx = \rho\, C_p T\, A\, u - \rho\, C_p \left(T + \frac{\partial T}{\partial x}\, dx\right) A\, u - \alpha\,(T - T_o)\, dx \tag{5}$$

This form can be simplified into:

$$\frac{\partial T}{\partial x} + u\ \frac{\partial T}{\partial x} = \frac{\alpha}{A\, \rho\, C_p}\ (T_o - T) \tag{6}$$

The analytical solution of the above formulas is:

$$T_x(t) = T_o + [T_i(t - \delta) - T_a] \exp(-\frac{\alpha}{A\rho\, C_p}\delta) \tag{7}$$

T_x is the outlet temperature, which refers to the customer (substation) supply or the generation return temperature. T_i The inlet temperature refers to the generation supply and the customer (substation) return temperatures. α is a function of the insulation thickness and the burring depth. δ is the heatwave interval delay between the customer and generation unit (Wang et al., 2017) and can be calculated as follows:

$$\delta = \int_{t-\delta}^{t} u\,(t)dt \tag{8}$$

Equations (7) and (8) could be further simplified while enhancing their ability to simulate the water's temperature estimation between the supply and consumption.

$$T_{cons}(t) = \alpha\, T_{sup}\,(t - \delta) + \beta \tag{9}$$

Where α and β are parameters estimated by regression, α is a function of pipeline length, velocity, and heat transfer coefficient. While β is a function of all the above and the outdoor temperature (Wang et al., 2017). The time delay (δ) is estimated by analysing the heat wave delay of the pipeline according to the following function:

$$\delta = \frac{1}{N}\sum_{j=1}^{N} \delta_j \tag{10}$$

Where N is the number of peaks and valleys in the data under study.

It was observed that one peak or valley in the supply temperature is followed by one at the customer side in fast succession (Lin & Hong, 2013). The heatwave delay, between generation and customer, can then be estimated by calculating the time it takes a local peak (a local temperature maxima) or a local valley (a local temperature minima) to be observed at the customer side after observing it at the production side in the supply pipe, and vice-versa in the return pipe. The number of time delays is then averaged depending on the available data. The following graph illustrates how the model auto detected the peaks and valleys of the supply pipe from a given data set.

It's specified within the developed model to limit the data selection to 21 peaks and 21 valleys based on the data available (the maximum number of peaks observed within a time frame of 200 hours was 25 in the return pipe. That choice was made due to practical coding conveniences; as illustrated below, the model captures the local peaks/ valleys by comparing its value to the nearby eight values to avoid assigning an unreal local peak/ valley. The model will then match the peaks and valleys of the production and customer temperatures to identify heat intervals that happen in a maximum duration of 6 hours between every two points.

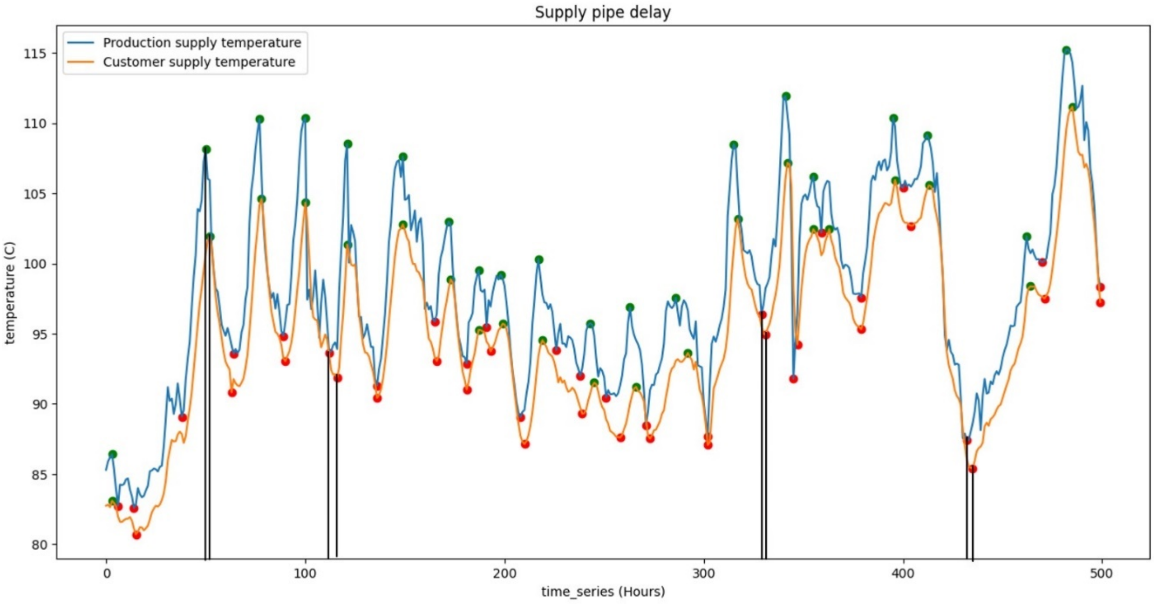

Figure 8 Peaks and valleys auto-detection by the model and delay calculation

That, however, isn't a general rule; the more data we feed into the model, the more accurate output would be obtained. However, comparing the turnout of multiple sampling points, this method requires only three representative points to converge into a reliable result. The auto-detection, automatic identification of the temperatures peaks and valleys in a given data set, was performed based on the function "argrelextrema" defined in Python's library "scipy. signal". The heat wave delay calculation was then performed according to the following algorithm utilizing a "*for* loop" that iterates over two Python arrays. The word "item" here refers to the timing of the occasion (peak/ valley) rather than the thermal value (temperature):

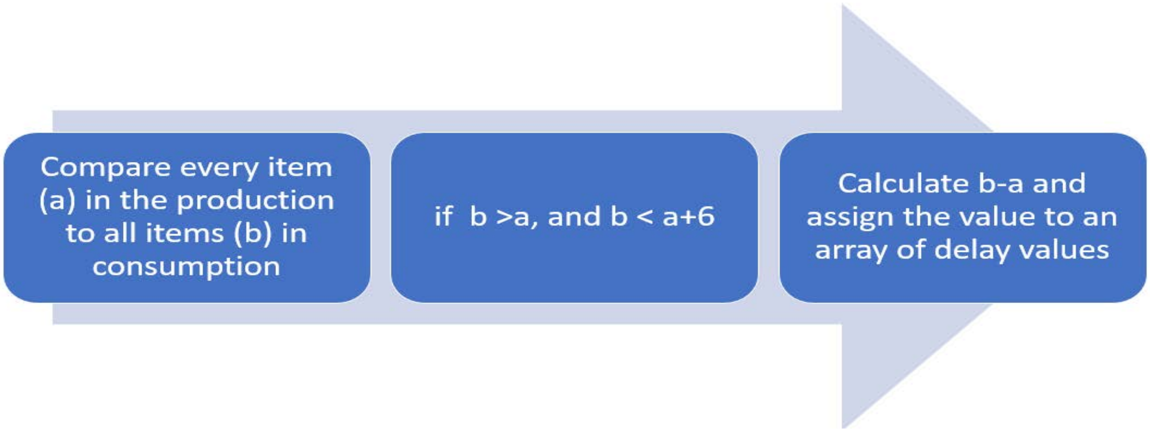

Figure 9 delay calculation based on the peak and valley timing in production/ consumption temperature profiles

Equation (9) could be written in the following form to reflect that measured data is discrete-time in the form of series data.

$$T_{cons}(k) = \alpha \, T_{sup}\,(t - \Delta) + \beta, k = \Delta + 1, \ldots, M \qquad (11)$$

Where k is the sampling time and Δ is a function of delay time; it is the closest integer to δ

$$\Delta = \begin{cases} [\delta], \delta + 0.5 \in \Delta \\ argmin \; ||\delta - x||^2_{x \in \Delta}, \delta + 0.5 \notin \Delta \end{cases} \qquad (12)$$

The delay parameters alfa and beta (parameters obtained by regression), alfa is identified by pipeline’s length, velocity, and heat transfer coefficient, while beta is determined by these elements and outdoor air temperature. Alfa and beta are estimated for both supply and demand pipes as follows:

$$\alpha = \frac{n\sum_{k-1}^{M-\Delta} T_{sup,s}(k).T_{cons,s}(k) - \sum^{M-\Delta} T_{sup,s}(k)\sum^{M-\Delta} T_{cons,s}(k)}{n\sum_{k-1}^{M-\Delta} T_{suup,s}^{2}(k) - (\sum_{k-1}^{M-\Delta} T_{sup,s}(k))^{2}} \quad (13)$$

$$\beta = \frac{1}{M - \Delta}\sum_{k=1}^{M-\Delta} T_{cons,s}(k) - \frac{\alpha}{M - \Delta}\sum_{k=1}^{M-\Delta} T_{sup,s}(k) \quad (14)$$

Once these variables are identified, the outlet temperature for the supply and return pipe can be determined:

$$T'_{cons,s} = \alpha\, T'_{sup,s}\,(k) + \beta, k = 1, \ldots, M - \Delta \quad (15)$$

And the dynamic heat loss:

$$Q_{loss,s}^{i} = C_p^i v_{cons}^{i}(k).\,[T_{sup,s}^{i}(k) - \alpha_s^i T_{sou,s}^{i}\big(k - \Delta_s^i\big) - \beta_s^i \quad (16)$$

The grid was simplified to a tree structure of a line type, and the hydraulic characteristics were then estimated by performing an energy balance:

$$\Delta E_s + \Delta E_r = Q_s - Q_d - Q_{loss,s} - Q_{loss,r} \quad (17)$$

Where:

ΔE_s : the energy change of the supply pipe between time (i) and (i-1) = $\Delta E_{s,i} - \Delta E_{s,i-1}$

The energy of the hot water at any given time (i) can be expressed as: ρ $C_p\ v_i T_i$, assuming that water is an incompressible fluid under the simulation conditions, and v_i is the volume flow rate.

ΔE_r : the energy change of the return pipe between time (i) and (i-1)

Q_s : heat supply by the production unit

Q_d : heat consumed at the customer's end

$Q_{loss,s}$: heat losses to the ground from the supply pipe

$Q_{loss,r}$: heat losses to the ground from the return pipe

3.4.2 Grid as a storage model

The second model was based on previous work done at Utilifeed AB, the grid structure was simplified, and the thermal/ hydraulic characteristics were then obtained. The basic model was developed to reflect the grid's behaviour, reduce its complexity, and provide in-depth analysis without much work upfront the model's operation. Insights of this model were aimed to be utilized in the temperature forecast process (under the conditions of fixed or variable supply temperatures). Moreover, the model can potentially optimize the supply temperature, evaluate the losses, and, when fed with sufficient hydraulic data, detect faults in the network. Several assumptions governed the development of this model:

Storage with perfect mixing: DH networks are a largely closed water system, with a great range in cities and towns (Niemyjski & Zwierzchowski, 2021). The DH pipeline, including those with complicated structures, could be considered a storage system. Mixing processes are conducted in many ways, and each method results in a specific change of state based on initial and final conditions of temperature and pressure (Smith et al., 2018). The classical operation method suggests that production units' heat supply varies, so heat supply is always equal to the demand (Hennessy et al., 2019). Putting such a theory into the context of the grid as storage implies that equilibrium conditions and outlet flow's characteristics can be obtained by applying the energy balance of mixing, considering the variation of volume at the inlet, outlet and storage capacity.

Volume flow rate is constant in the supply and return pipe: The grids under investigation are high-temperature district heating (HTDH). Such grids usually operate at a temperature range of 70 ^{o}C to 120 ^{o}C, and have a return temperature between 45 ^{o}C to 65 ^{o}C (Thalmann, et al., 2018). The pressure at the last grid point should be 0.5-1.5 bar higher than the steam pressure at the maximum network's temperature (Thalmann, et al., 2018). Water under such conditions could be assumed to be incompressible, and therefore, volume can be considered constant. Such an assumption can be generalized to cover all tree-structured networks and mesh structures with interconnections in the network (Frederiksen & Werner, 2013b). However, that's not the case when a circulation pump is installed within a meshed network, either on supply or demand, a flow rate variation would then be expected at some intersections (Frederiksen & Werner, 2013b).

Aggregation of heat loads: The model utilizes the aggregated customers' heat loads as an input value. The process takes into consideration a variety of considerations (Frederiksen & Werner, 2013b):

- Seasonal heat load variations
- Heat load weather dependence
- Daily heat load variations
- Heat load consumption
- Short-term heat load forecast

The grid is assumed to be a simple two pipes (supply/ return) with the aggregated heat supply and demand at the two sides. The model considers the grid to be buried underground; the supply and return pipes, which have the same size, are installed next to each other. The following figure presents the schematic grid structure studied by this model.

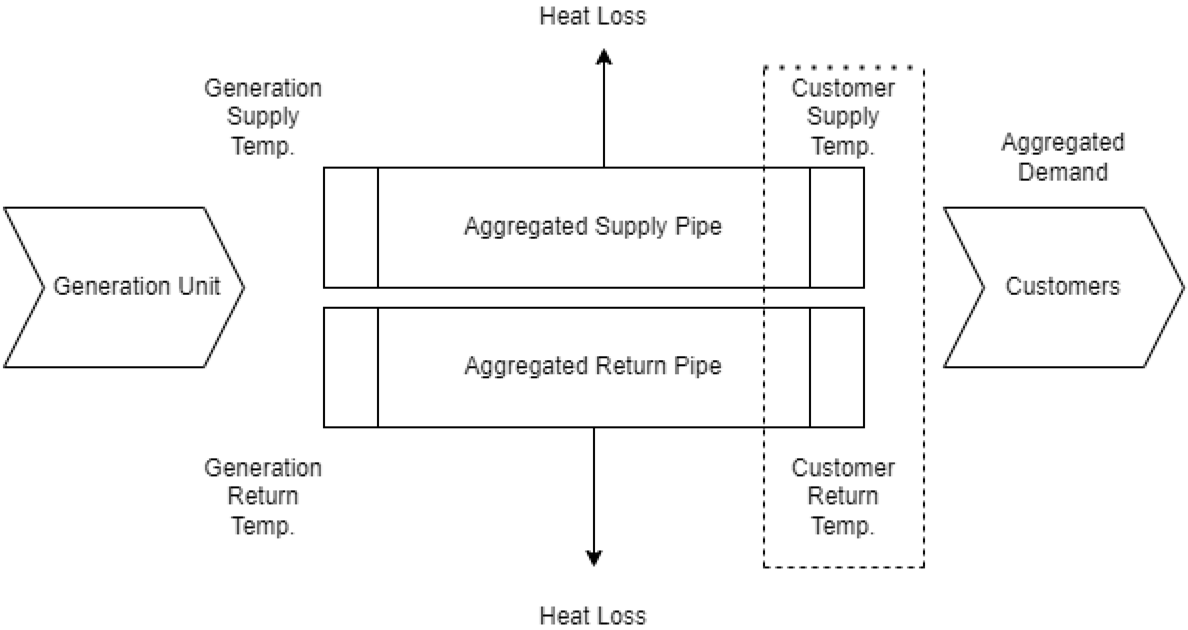

Figure 10 Simplified structure of DH system

The first step in the calculation was to estimate the heat losses; a method suggested by Werner (Frederiksen & Werner, 2013b) was followed. The heat resistance of the two pipes consists of three main contributors: the insulation resistance, the ground resistance and the coinciding temperature fields (mutual heat transfer between supply/ return temperature.

The heat loss from the supply pipe is given by:

$$Q_{loss,s} = Q_{loss,so} + Q_{loss,sr} \tag{18}$$

Where:

$Q_{loss,so}$ = heat losses from the supply pipe alone [W]

$Q_{loss,sr}$ = heat losses from the supply pipe to the return pipe [W]

Equation (18) can be written as follows:

$$Q_{loss,s} = L.\pi.d.\left[\left(R_g + R_{ins}\right).T_s - R_{cn}.T_r\right]/[\left(R_g + R_i\right)^2 - R_c^2] \tag{19}$$

Where:

L = route length for pipes (halfpipe length) [m]

d = outer pipe diameter, the temperature drop through the wall is small, and it can be neglected [m]

R_g = ground resistance [m^{2}K/W], is given by the equation

$$R_g = \left(\frac{d}{2\lambda}\right).\ln\left(\frac{4h}{D}\right) \tag{20}$$

R_{ins} = insulation resistance [m^{2}K/W]

$$R_{ins} = \left(\frac{d}{2\lambda_{ins}}\right).\ln\left(\frac{D}{d}\right) \quad (21)$$

R_c = coinciding temperatures [m^{2}K/W]

$$R_c = \left(\frac{d}{2\lambda}\right).\ln\left[\left(\left(\frac{2h}{s}\right)^2 + 1\right)^{0.5}\right] \quad (22)$$

T_s = Temperature difference between the average supply temperature profile and the ground temperature

T_r = Temperature difference between the average return temperature profile and the ground temperature

D = outer insulation diameter [m]

h = distance from pipe centre to the ground surface [m]

s = difference between pipe centre [m]

λ = ground heat conductivity [W/m.K]

λ_{ins} = insulation heat conductivity [W/m.K]

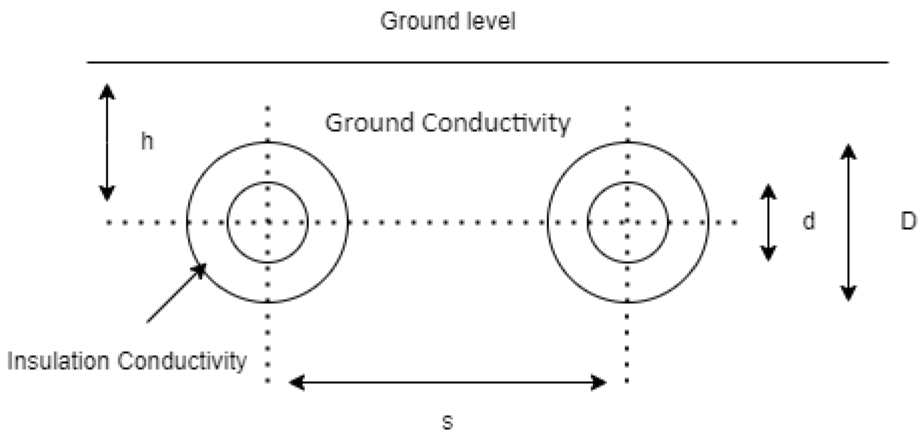

Figure 11 Heat transfer model adopted from (Frederiksen & Werner, 2013b)

Heat losses from the return pipe:

$$Q_{loss,s} = Q_{loss,so} - Q_{loss,sr} = L.\pi.d.\left[\left(R_g + R_{ins}\right).T_r - R_{cn}.T_s\right]/\left[\left(R_g + R_{ins}\right)^2 - R_c^2\right] \quad (23)$$

The next step is to determine the outlet temperature, which can be done by utilizing the assumption of perfect mixing. The outlet temperatures: the customer supply temperature and the production return temperature could be estimated by the weighting average of the entire network's volume and temperature and the current volume/ temperature supplied by the generation unit or, in the case of return pipe; the left the primary side of customer's substation. The equation will utilize the thermal and hydraulic parameters obtained at the last time step (t-1) to estimate the thermal parameters at the current time step (t) as per the following equation:

$$T_{out,t} = \left(\frac{v_{t-1}}{v_{tot}} \, . T_{sg.t}\right) + \left(\frac{v_{tot} - v_{t-1}}{v_{tot}} \, . T_{eq}\right) - \; Q_{loss,t} \qquad (24)$$

Where:

v_{tot} = total volume of either supply or demand pipes [m^3]

$T_{out,t}$ = temperature at the network outlet, in the supply pipe, it is the customer supply temperature at the primary side of the substation, while in the return system is the production's return temperature [C]

v_{t-1} = volume flowrate at the current time step (t-1) [m^3/hr]

v_{t-1} = volume flowrate at a specific time step (t-1) [m^3/hr]

T_{eq} = the temperature of the equilibrium status at the last time step is usually equivalent to the temperature at the pipe outlet at the previous time step [C]

$Q_{loss,t}$ = heat losses at time step (t) [KJ] is calculated as ρ $C_p v \; (T_{pipe} - \; T_{ground})$

The current volume flowrate is then estimated based on the equation of overall energy balance of the system:

$$\Delta E_s + \; \Delta E_r = Q_s - Q_d - Q_{loss,s} - Q_{loss,r} \qquad (25)$$

Each time step's output shall be considered an input to the next step, therefore creating a calculation loop for the time frame under study.

3.5 Code implementation

The theoretical model, upon completion, was translated into a code to complement it with some essential features, i.e., computational power and intuitiveness. The developed model handles thermal and hydraulic parameters of the DH network (in both supply and return pipes); Python, an open-source and user-friendly programming language, adds an enormous computation power that processes such a data set in an efficient and fast manner.

Python emphasises readability, minimum entry barriers, and an extensive environment of open-source tools. All users; scientists, researchers, software engineers, and beginners—employ these benefits and choose Python to run their projects (Muller, 2021). In addition, Python has a long history and high level of adoption, enabling users to access a variety of third-party tools and Python sets, including standard libraries. Knowing these tools and libraries, developing Python projects is much easier for all users with different backgrounds(Muller, 2021).

PyCharm, an intelligent code editor, was used for code completion, visualization, and inspection. The tool provides remarkable insights in the area of error highlighting and fixing and automated code refactoring and navigation capabilities. The editor was used within 'the Conda; environment; a package and environment management system that runs in many platforms; it enhances the model visualization and complements it with the suitable packages for python edition.

3.6 Model validation:

One of the essential steps in modelling is results validation, and this step has the following objectives (Farzaneh, 2019):

- Determine whether the model can satisfy the requirements of dealing with a specific problem.
- Check whether the simulation produces satisfactory results within a reasonable timeframe.

- Check whether the model's results allow for a comparison between different investigation methodologies.
- Benchmark the model against the actual measured data to determine its accuracy
- Run the model with different data that reflects significant changes to test its robustness and resilience.

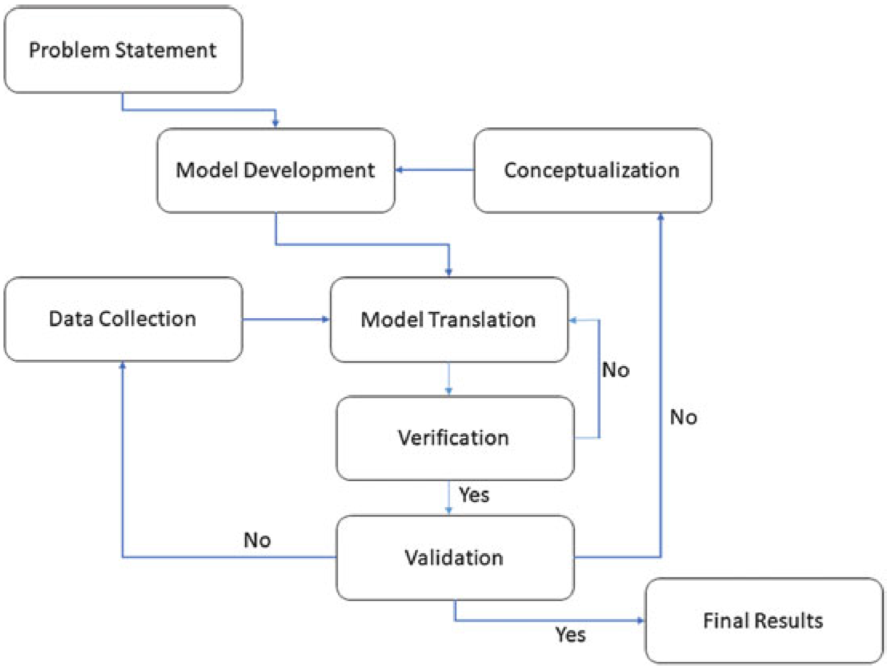

Figure 12 Simulation model development adopted from (Farzaneh, 2019)

4. Results

The two models, delay analysis and grid as storage, were developed, coded, and loaded with real-time grid's data (the presented data and results are measured hourly throughout the year. Both models' performance was then benchmarked against reality to identify their feasibility to reflect the gird's insights.

4.1 Overview

The first research question motivated the search for a suitable characteristic of the modelling work and therefore narrowed down the modelling approach which could be used in this thesis. Four KPIs; accuracy, ease of use, robustness & resilience in addition to data intensity were found to be relevant to the scope of this thesis. Subsequently, a modelling approach was developed, and two modelling procedures were then constructed: grid as a storage and delay analysis. The modelling parameters: customer supply and generation return temperature volume flowrate and heat losses were estimated by the dynamic modelling and then evaluated against the real grid performance to address the second research question. Lastly the model run with the purpose of providing some grid insights for the purpose of optimization and flexibility.

4.1 Delay analysis model

The fundamental element of the model was to capture the delay of the heatwave from the production unit to the customers' substations. The model initially utilized the grid's data during January. 2019, the average heatwave delay for that period was 2 to 3 hours for the supply pipe and 1.5 to 2.5 hours for the return pipe. There were a couple of parameters that influenced the delay calculation:

- Calculation period: The model started calculating the delay for a specified period of time within the simulation duration to capture the grid's performance accurately. However, accurate results were obtained by estimating the delay for a shorter duration of time. The current results present the case of calculating the delay for one week and then generalizing the delay value for the coming month.
- Data trend: It was observed that the delay parameters are sensitive to several factors related to pipeline operation parameters and outdoor weather. For instance, a week in

February can't be used to calculate a delay pattern and use it to simulate the thermal grid behaviour in June. Moreover, within a period of a similar performance trend, choosing a non-representing period for delay calculations, for example, three consecutive nights with peak energy consumption, would typically lead to less accuracy.

4.1.1 Thermal Modelling

The delay analysis model was "trained" to calculate the delay factor from the 1st of January.2019 to the 8th of January.2019. The model then simulated the thermal behaviour of the DH grid understudy and generated the results presented in the following figures for both supply and return pipes. The first characteristics obtained via this model were the customers' supply temperature (an average value of all customers aggregated at a single point) calculated based on the generation supply temperature and the delay factors alfa and beta as introduced in the methodology chapter. Likewise, the generation unit return temperature was then calculated based on the customers' return temperature and the delay parameters of the return pipe.

Parameter	Supply pipe	Return pipe
Heatwave delay	2.17 (hours)	1.957 (hours)
Alfa	0.986	0.9703
Beta	-0.00506	-0.00085

Table 1 Delay analysis parameters (1-8 /January .2019)

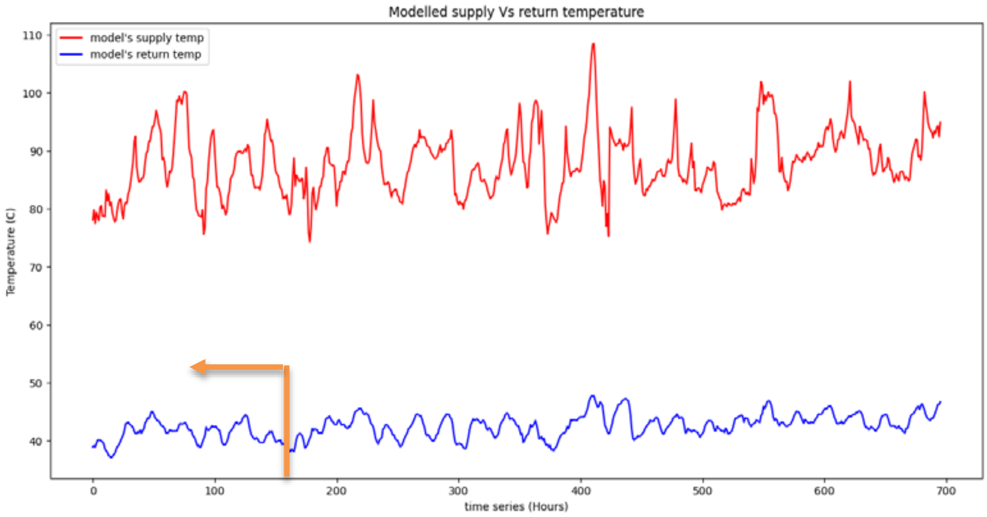

Figure 13 Modelled customer supply & generation demands temperature, the arrow indicates the training period (1-30 /January .2019)

The model's output was then compared to the actual parameters' measurements for the duration under study (700 hours). The following graphs demonstrate the modelled customer supply and generation return temperatures compared to the actual values.

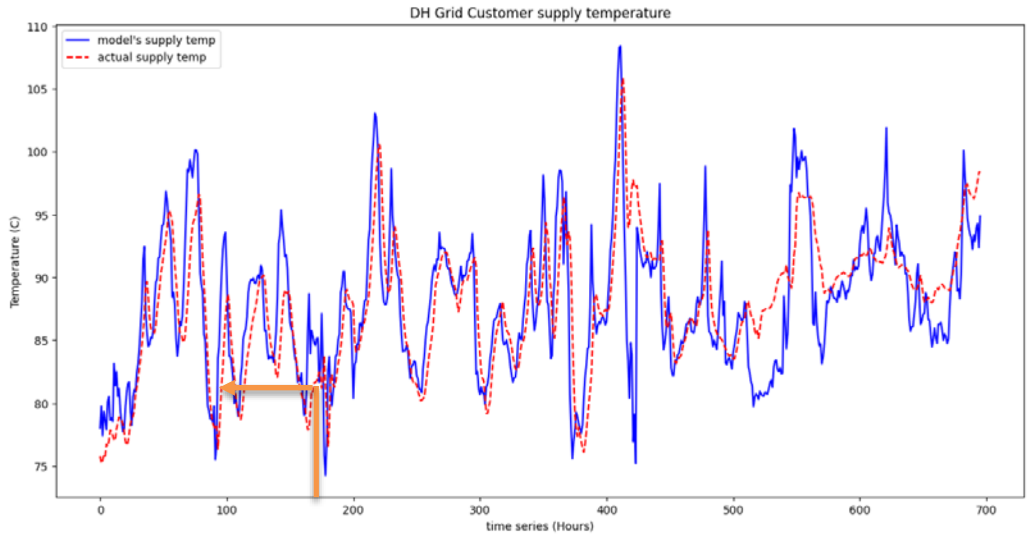

Figure 14 modelled VS actual value of customers' supply temperature, the arrow indicates the training period (1-30 /January .2019)

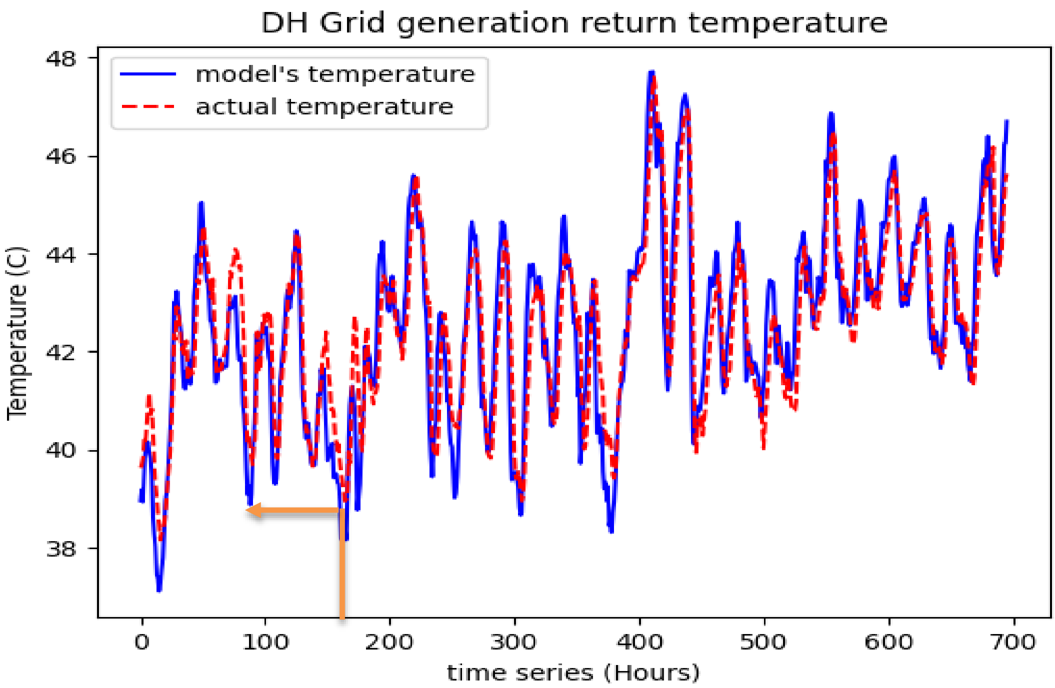

Figure 15 modelled VS actual value of generation return temperature, the arrow indicates the training period (1-30 / January .2019)

It was observed that the modelled temperature in both supply and return pipes followed the trend of the actual data throughout the simulation period. In the case of the customer supply temperature, a higher level of fluctuation is observed after hour 400, which can be due to training duration ability, data trend, and temperature during the simulation. On the other hand, the return pipe was modelled with a high level of accuracy as the modelled data matched the actual measurements reasonably well, and the absolute temperature difference between the real and modelled values was kept under 2.5 °C. The table below summarizes the accuracy indicators of the modelled thermal parameters.

Indicator	Customer supply temp.	Generation return temp.
Average temperature deviation	3.048 (°C)	0.6936 (°C)
Mean temperature deviation	3.542 (°C)	1.0695 (°C)

Table 2 Modelled temperatures' deviation

The model then estimated the heat losses to the ground-based on the measured delay parameters and the calculated temperatures. The network's heat loss during January 2019 was found to be within 2.5 % - 4% of the energy produced, with an average value of 3% of the total production.

Such an estimation could be assessed with reference to the typical annual distribution losses value for a Swedish network ranging between 10% - 12% (Vesterlund et al., 2013). Another estimation of 7% is given by (Gustafsson et al., 2009). That, however, includes all distribution losses from different grid elements, i.e., pipes, pumps, and fittings. This modelling approach focuses on losses without capturing the detailed geometry of the grid. The delay model focuses on a relatively short-term simulation of the grid, therefor, annual grid losses wasn't part of the current modelling work. The average grid losses during this period was 3% of the total production

Figure 18 illustrates a remarkable correlation between heat losses and energy consumption at the customers' substations. Furthermore, the behaviour of the losses followed the customers' consumption trend throughout the simulation period with remarkable consistency. This behaviour is illustrated in the following figure: The heat losses ramp up almost instantly following the local maxima of consumed energy and decrease sharply during local minimum energy consumption.

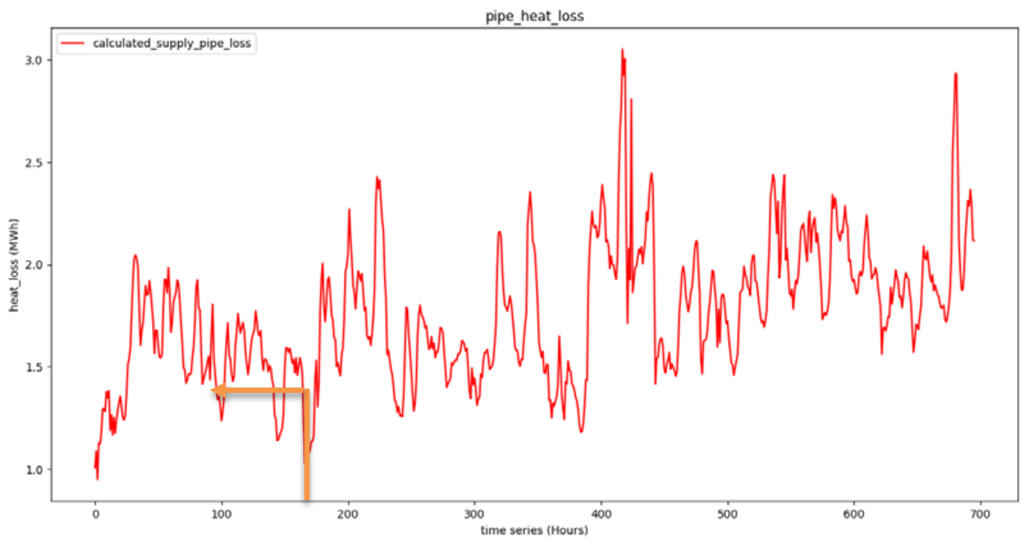

Figure 16 Estimated heat losses Mwh, the arrow indicates the training period (1-30 /January .2019)

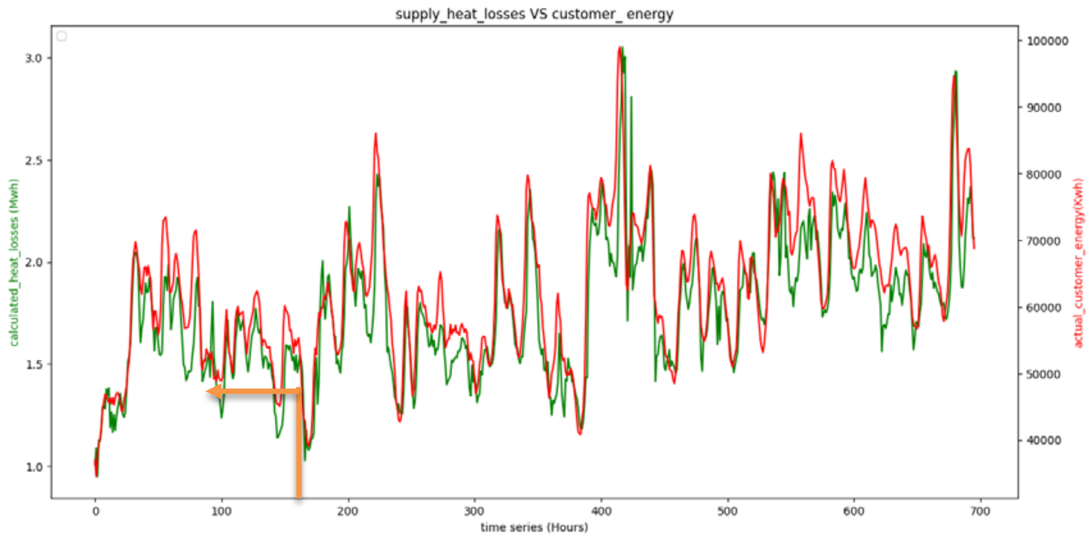

Figure 17 Supply heat losses VS consumed customer energy, the arrow indicates the training period (1-30 /January .2019)

One of the significant characteristics of the thermal performance of the district heating systems is the temperature difference at the substation's primary side. It refers to the difference between the supply and return temperatures at the substation. Lowering the return temperature is usually associated with efficiency enhancement for the generation unit. Moreover, low supply temperature is an optimization subject as it contributes to lowering operating costs and reducing heat losses. Therefore, a large delta T results in a lower pumping work for circulation, and it also permits the use of smaller pipe diameters during the design phase (Frederiksen & Werner, 2013b). The current model introduces the possibility of evaluating the delta T by estimating the supply temperature, given that demand could be forecasted. The following graph illustrates the delta T as given by the model.

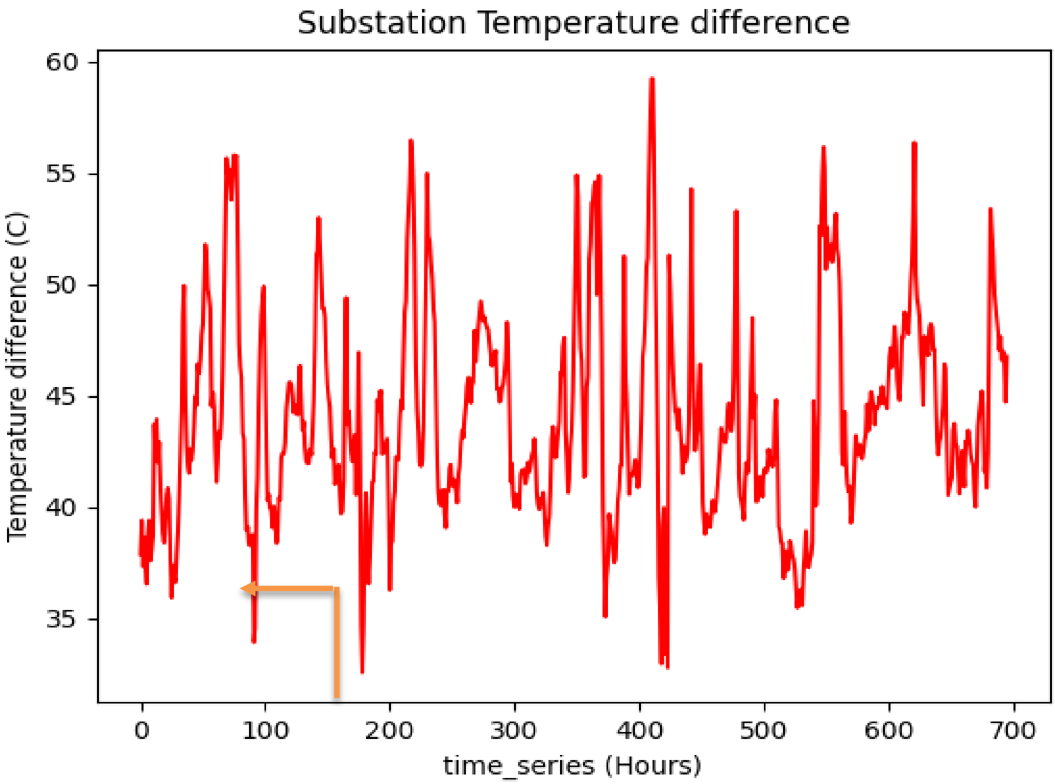

Figure 18 Modelled delta T at the Customer's substation, the arrow indicates the training period (1-30 /January .2019)

4.1.2 Hydraulic Modelling

The model then estimated the hydraulic behaviour of the grid, and the flowrate was determined to reflect the hydraulic characteristics. This study doesn't include pressure performance due to the unavailability of accurate grid geometry and pressure measurements. The flowrate followed the energy consumption pattern; the flowrate ramped up once the consumption increased and vice versa. As explained in the method chapter, the volume flowrate was calculated by applying an energy balance equation around the Customer's substation, implying the error of estimating the customer supply temperature will be cascaded down to the flowrate estimation. Therefore, the deviation of modelled flowrate deviates to a greater extent during the highest energy consumption peaks. The average deviation of the modelled flowrate was 87 (m^3/hr). The modelled volume flowrate was then compared to the actual flowrate as illustrated in the following figure:

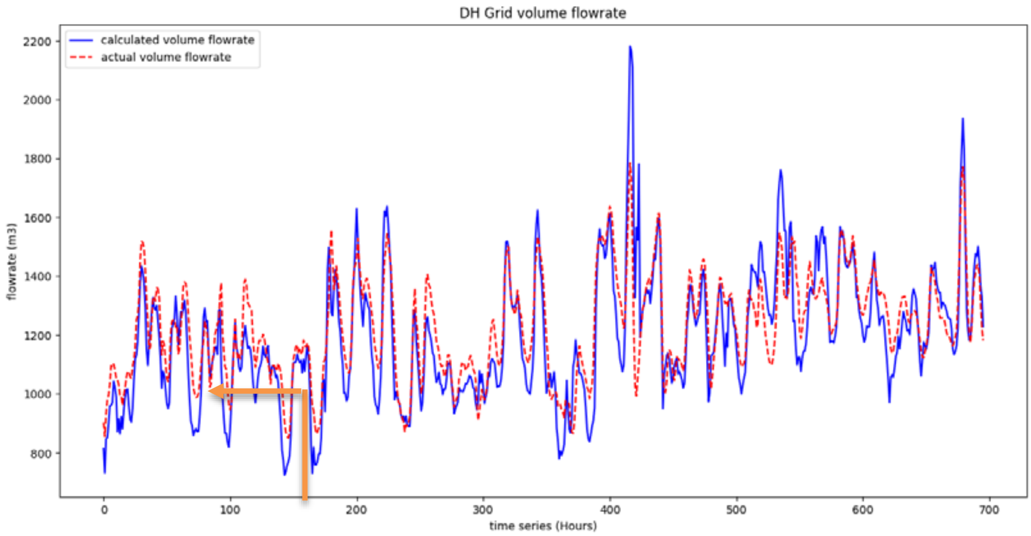

Figure 19 Modelled vs actual Volume flowrate, the arrow indicates the training period (1-30 /January .2019)

4.2 The grid as a storage model

This model simulated the same period as the previous one; January.2019. It initiated capturing the grid's performance by estimating the heat losses in the piping system. To do that, a hypothetical grid was constructed; the below table presents the chosen geometry f this grid:

Parameter	8"	6"	4"
Pipe size (DN)	200	150	100
Depth from pipe centre (m)	0.7	0.7	0.7
Distance from pipe centre (m)	0.5708	0.52	0.466
Pipe outer diameter (mm)	0.2191	0.1683	0.1143
Insulation outer diameter (mm)	0.355	0.28	0.225
Insulation heat conductivity (W/m.K)	0.67	0.633	0.49
Ground heat conductivity (W/m.K)	1.5	1.5	1.5
Pipe length (m)	10,000	15,000	8,000

Table 3 Hypothetical grid geometry

4.2.1 Thermal Modelling

The model estimated the heat losses for both supply and demand pipe as illustrated in the following graph. The losses were found to be correlated to the energy consumption at the customer substation and within the same order of magnitude compared to the results from the delay analysis model.

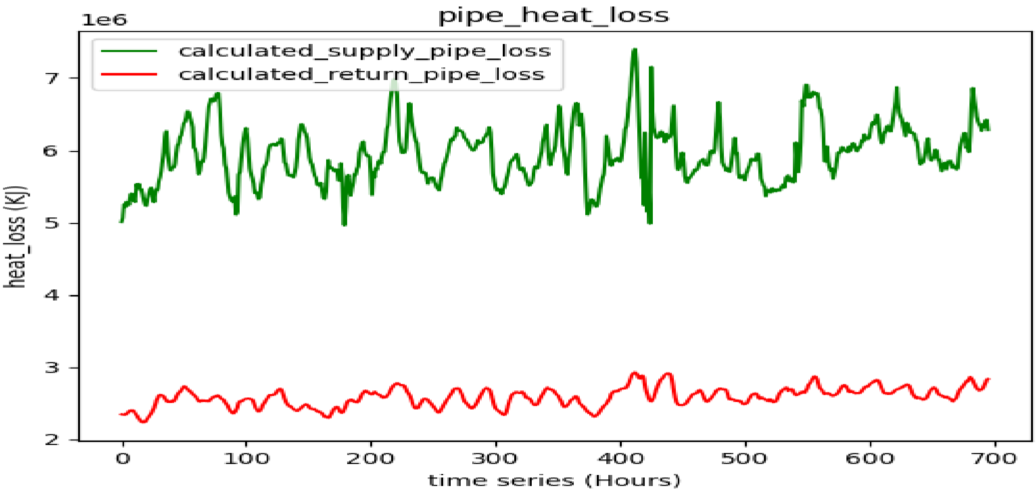

Figure 20 DH Grid heat losses KJ, (1-30/ January .2019)

The average grid supply losses were found to be around 3% of the produced heat, and the absolute losses value was found to follow the customers' heat energy consumption pattern. Therefore, the supply losses are usually a significant parameter to the grid owner. However, since this model estimates the output temperature based on the heat losses, both supply and return pipes' losses are essential to calculate the customer supply and the production return temperatures.

The supply and return temperature were then simulated, and comparing them with the measured data, both temperatures followed the behaviour of the actual values. The deviation is summarized in the following table:

Indicator	Supply pipe	Return pipe
Average temperature deviation	2.92 (°C)	0.85 (°C)
Mean temperature deviation	2.78 (°C)	1.65 (°C)

Table 4 Modelled temperatures' deviation

The following figures give the temperature simulation in comparison to the actual values:

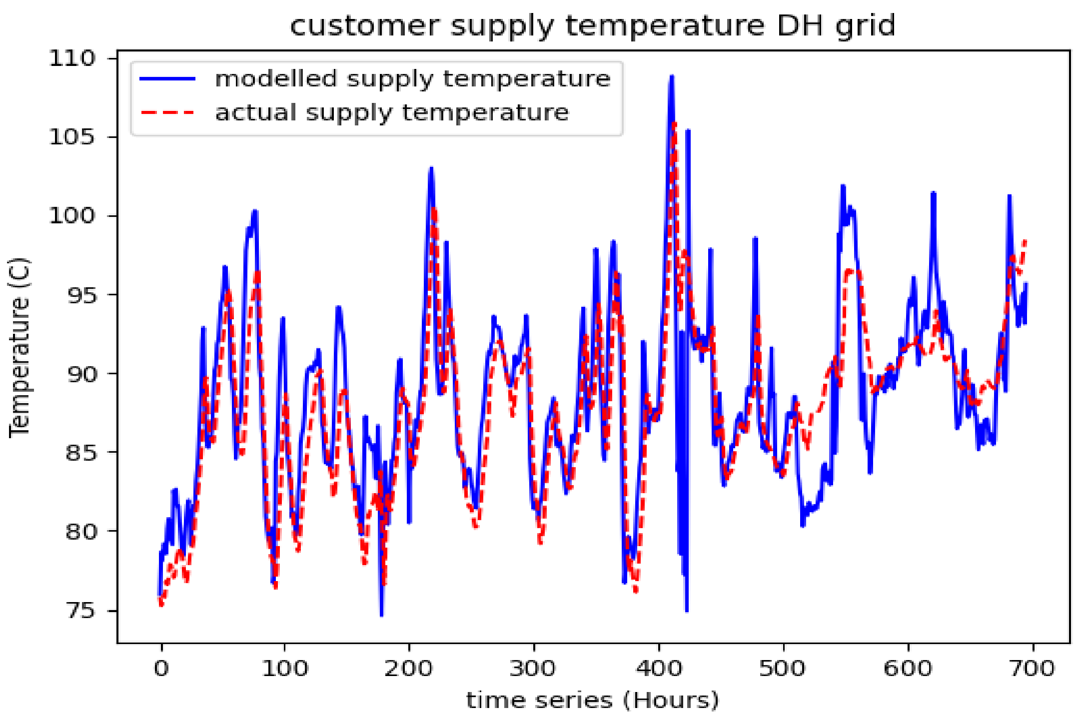

Figure 21 Modelled customer supply temperature (1-30 /January .2019)

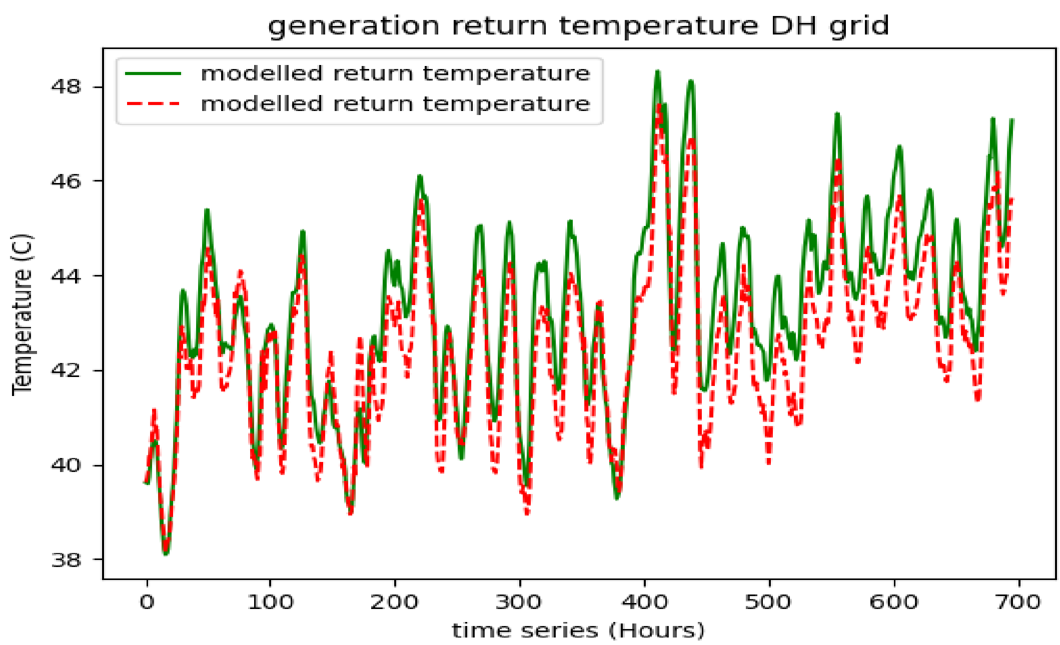

Figure 22 Modelled generation return temperature (1-30 /January .2019)

The absolute deviation of modelled customer supply temperature was generally kept below 5 ^{o}C with occasional spikes to 10 ^{o}C, and to 20 ^{o}C at a single event associated with a steep ramp-up and peak heat energy consumption. On the other hand, the return temperature had an absolute error of below 1.5 °C. The temperature difference around the substation varies between 30 °C to 60 °C, a similar behaviour to the delay analysis model results.

4.2.2 Hydraulic modelling

This model then presented the hydraulic characteristics of the grid by estimating the volume flowrate in the grid by performing energy balance on the primary side of the Customer's substation. The modelled values had an average deviation of 98 (m^3/hr). Compared to the delay model, this one captured the hydraulic behaviour with more accuracy except for the flowrate peak occasions, that's usually associated with the energy consumption peaks. In peak durations, the delay model captured the grid behaviour with less absolute deviation from the actual volume flowrate compared to the second model. The modelled volume flowrate was then compared to the actual flowrate as illustrated in the following figure:

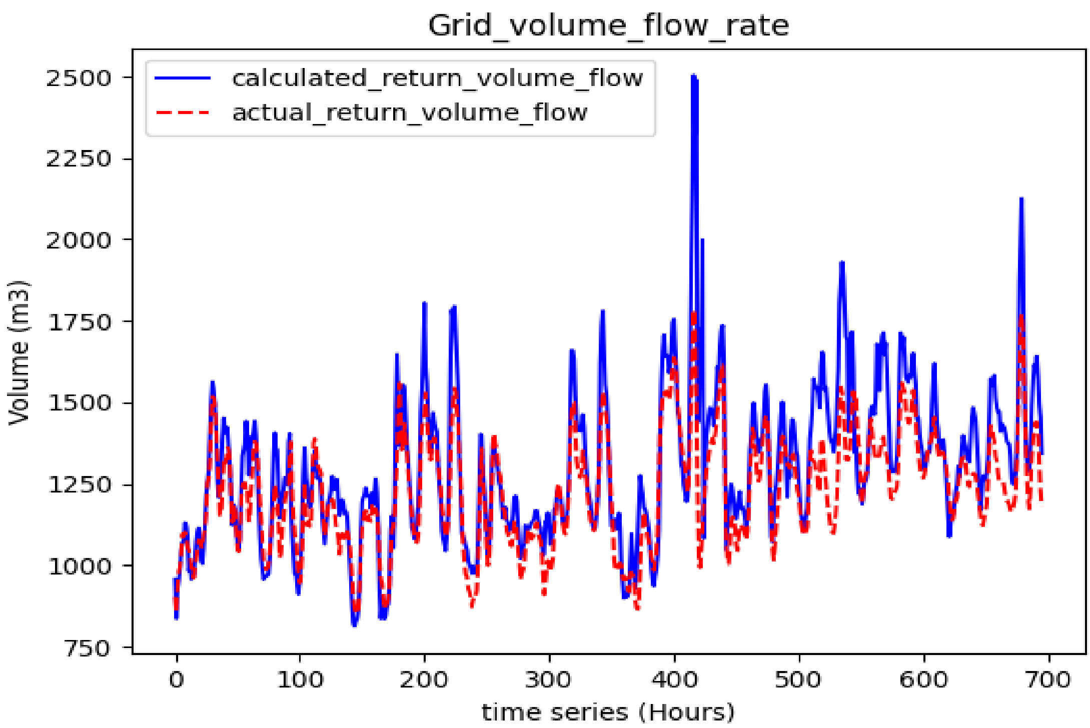

Figure 23 DH Grid modelled volume flowrate VS actual (1-30 /January .2019)

4.3 DH Grid modelling insights

This section discusses some insights offered by the DH model, it focuses on the potential use of the model for production optimization and flexibility identification by utilizing the model's thermal and hydraulic results.

4.3.1 Optimization

The presented models were able, with reliable accuracy, to capture the behaviour of the district heating network and therefore be used for a variety of purposes. The optimization of both design and operation of DH systems is a potential use of the DH models. There are generally two aspects of optimization: the thermal part focuses on the supply temperature at the Customer's substation. The hydraulic part focuses on the volume flowrate related to the pumping duty. The ability to simplify and model the operation of the DH grid introduces the ability to optimize these two parameters, given that a reliable forecast of the demand is available. Figure 24 and 25 present the behaviour of the supply temperature and flowrate at different energy demand levels, the highlighted area presents different patterns of production at different occasions.

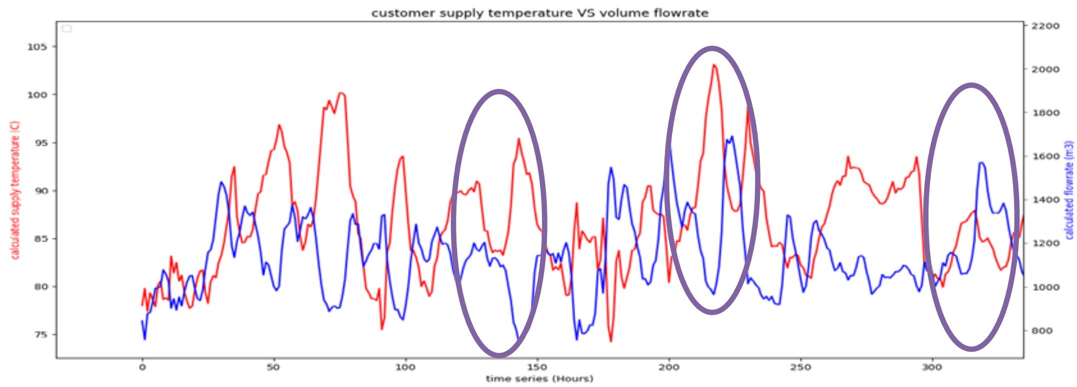

Figure 24 Volume flowrate VS customer supply temperature (1-30 /January .2019), the ringed area illustrates the supply temperature and volume flowrate response to the demand local maxima and minima values

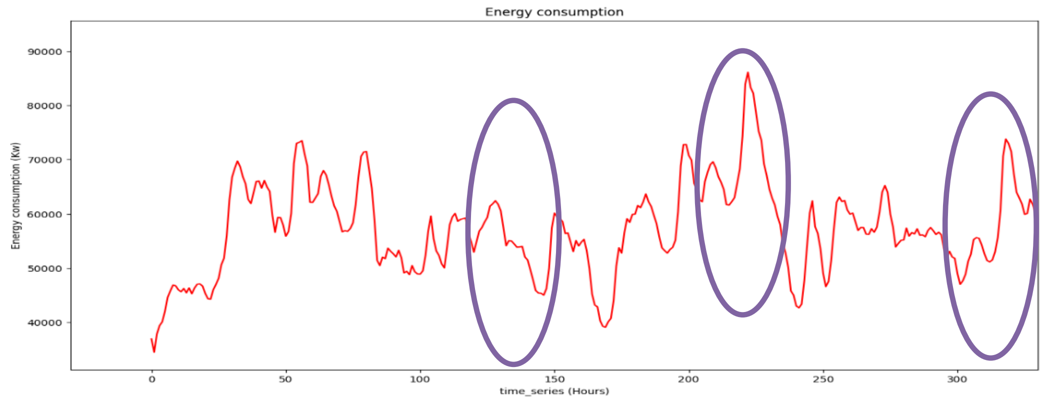

Figure 25 Energy consumption (1-30 /January .2019), the ringed area represents the customer's demand at different occasions

The model predicts the behaviour of the customer supply energy and volume flowrate at different levels of energy consumption and identifies how the generation unit modifies these The delay analysis model presents the ability to forecast the customer supply temperature based on the generation temperature, a variable linked to the generated energy and the forecasted customers' heat consumption.

4.3.2 Flexibility potential

As presented above, there're two variable respond to the change of energy demand i.e., supply temperature and volume flowrate. The DH owners can utilize the simulation ability of this model to establish the production strategy, i.e. increase the cost competitiveness of the heat produced and maximize the value of the heat produced.

The DH model also presents the potential of utilizing the grid storage capacity for flexibility provision. Conventionally, in a high-temperature district heating system, the produced heat should exceed or be equal to the demand. Therefore, supply-demand energy matching is an important performance indicator for the DH systems operation. The primary function of the district heating network is to deliver heat to customers; every network has a designed thermal capacity (designed temperature range) and hydraulic capacity (designed total network volume and volume flowrate). The DH models present, with reliable accuracy, the occasions when the system is operating below its rated capacities. It also shows the delay of a thermal wave from supply to demand. Coupling this insight with a forecast of the demand forecast, the model can then present occasions where the grid could be used as a mean of short-term thermal storage for demand's peak shaving. Figure 26 and 27 presents the temperature and volume flowrate of the supply pipe at different demand levels, while the highlighted area present occasions with potential storage capacity in the grid right before a peak of the heat demand

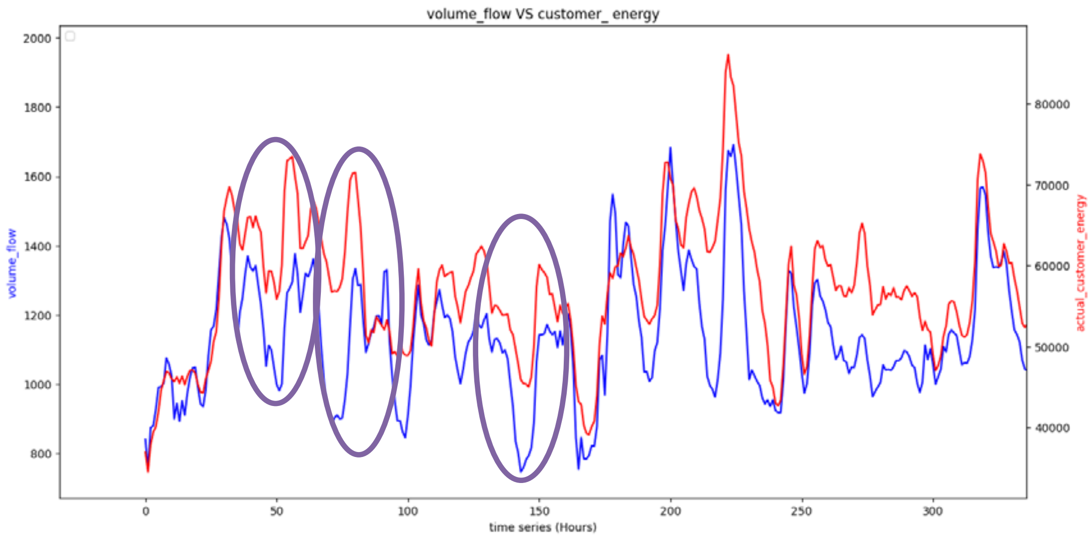

Figure 26 Volume flow VS customer energy demand (1-30/ January .2019), The ringed area illustrates the interval of when the volume of the grid is partially utilized followed by a high demand period

The availability of heat storage is a prerequisite factor to identifying the flexibility potential for the grid. It's, however, insufficient to confirm it. The electricity demand, and therefore electricity prices, should be coupled with the grid when identifying the flexibility potential.

5. Discussion

This chapter draws discussion points about the modelling work covered in this thesis. Modelling is about simplifying reality; therefore, this chapter addresses the variables and parameters excluded. Furthermore, the discussion considers the assumptions made to build the theoretical model and their impact on the model's performance and how they influenced the obtained results. Furthermore, the discussion highlights possible future work.

5.1 Modelling approach

The delay analysis model is based on the heat transfer study for a finite element of the DH grid, enabling a heatwave analysis of the fluid between supply to the customer. Therefore, it doesn't consider the grid geometry, i.e., pipes lengths, sizes, the material of construction and insulation. With no complex or computationally intensive preparation upfront, such an approach can be implemented for tree-structured DH networks that have a specified point of heat injection. Setting up the model would be particularly complicated for a mesh-structured DH network, which interconnection between different grid segments with booster pumps to ensure the reliability of the heat waves analysis.

The grid as a storage model, on the other hand, relies on the grid geometry to estimate the distribution losses. It then calculates the outlet temperatures as a weighted average and the volume flowrate based on energy balance. The model considered the grid as a line form of the tree-structured network where the larger pipe was connected to the production unit and the smaller sizes attached to the customers. In reality, tree-structured DH networks have a more complex geometry that could be reduced to a more straightforward form with various computational methods (Larsen et al., 2004). Nevertheless, the line structure provided reliable insights and estimated the heat losses to the correct power of magnitude. First, however, the existing grid geometry should be obtained and simplified to calculate the actual losses.

Both modelling approaches have a calculation step of one hour; the delay model currently estimates the heat wave delay based on the available hourly operation data, which implies less detection of peaks and valleys and, therefore, limited ability to identify the delay. Upon the availability of a more frequent measurement (e.g., minutes), the delay parameters would be detected more accurately, improving the estimation of thermal and, subsequently, hydraulic parameters. On the other hand, the grid as storage assumed a perfect mixing in the grid; calculating the outlet temperature as a weighted average of the current and last time step values implies the timestep itself is sufficient to reach the ideal mixing point. The perfect mixing condition won't be met if the calculation step is inadequately short.

Both models dealt with an aggregation of supply and demand at single points, a more detailed insight of a large-scale network could be obtained if the grid is divided into central regions connected to the same generation unit. Therefore, the result would be more relevant to the actual condition related to each local area.

The models didn't consider pressure drop estimation due to the unavailability of exact grid geometry. It's, however, worth mentioning that it is a parameter of a particular significance to the grid operation as it could contribute to optimizing the pumps operation and leak detection.

5.2 Inputs & assumptions

The main inputs to the modelling work are the production supply temperature, the customer return temperature, and the forecasted demand energy at every time step. Modelling a large-scale DH network, it should be expected that some measurements aren't accurate due to several reasons, e.g. meters aren't calibrated, or they need maintenance. The presented models in this thesis deliver accurate results unless there's a persistence data measurement error; a data sanity check could be added to ensure the relevancy of the modelled data. This scope, however, is not part of the current project. The grid as storage had a couple of assumptions to develop a simple model; the first is that a DH grid works similar to a storage with a perfect mixing, implying that the physical and chemical properties are homogeneous throughout the grid volume. This is connected to the second assumption; the temperature of the supply pipe at any given time is assumed to settle to the customer supply temperature. The same concept is applied to the return pipe, where the temperature settles to the production unit return temperature. These assumptions consider a typical behaviour of the temperature heat waves at any given time, as it simplifies the heat transfer behaviour and subsequently the temperature gradient for modelling. A variety of studies have already addressed transient conditions and heat transfer phenomena in pipelines. It would be crucial to update the model to capture the exact behaviour of the heat transfer in the pipeline.

Additionally, for simplification purposes, both models considered the chemical properties of water, i.e., specific heat capacity and total volume, as a constant value. They also assumed that water is an incompressible fluid under the operation conditions of the DH grid as long as the density change is less than 5%. When extending the scope of the modelling work to cover a longer duration and much more fluctuation, it's essential to consider the dynamic nature of these parameters and estimate them as a function of the temperature of the operation conditions.

5.3 Results and models' performance

This section evaluates the output of the two models and offers insights into their performance under different conditions. In addition to that, the following discussion presents the absolute deviation of the models from the actual behaviour of the grid.

5.3.1 Delay Analysis model

When benchmarked against reality, the two models were able to generate an accurate simulation of the thermal and hydraulic performance of the DH network. The delay analysis model was proven to be simpler to set up and run than the grid as a storage model where more details were to be considered when estimating the heat losses. Furthermore, the delay model took advantage of the heatwaves peaks and valleys to generate a pattern of the heat delivery, which was then used to estimate the thermal properties of the grid. Unlike the grid as a storage model, the delay model was built with the input data (production supply temperature, customer return temperature, and forecasted energy demand), and the delay factor which was estimated based on the available data of the customer supply temperature and generation return temperature for a relatively short duration, in the presented results one week of estimation and one month of the simulation were presented. For the duration of one Winter week, some generation peaks are expected, the peaks and the valleys were limited to 8 points for each temperature value. That was done to eliminate misleading peaks/ valleys which is being autodetected by the model and facilitate the comparison process that the model does to capture the delay factors; the arrays of customer and production temperatures should have the same length when the model compares them.

It is worth noting that it is possible to estimate the delay for a longer duration to get more accurate results. However, since it's known that the delay detection is impacted by the length of the duration, in addition to the ability of this period to reflect the data trend over the simulation period, it was observed that an adequate number of points, starting from 3 points, would possibly generate accurate results. Therefore, since the targeted simulation period is one month, a short and reflecting delay-estimation duration is more efficient than a prolonged duration that can slightly enhance the calculation. Although one point is to be considered here, more frequent measurements, the current dataset was generated hourly, would be a better fit in the model as it will provide more details for a reality-capturing duration. Choosing the suitable interval for delay estimation was done based on simple criteria; a graphical representation is made for the estimation period, and occasions with clustered peaks and valleys are avoided. Likewise, periods with no local peaks and valleys were also avoided. The modelling work could be further improved by developing an algorithm to identify the suitable delay- estimation period based on a predefined simulation span.

5.3.2 Grid as storage

On the other hand, the grid as a storage model started as a steady state model. It generated converging results, which are then used as an input to the second calculation step and likewise up to the end of the modelling period. As a result, the results of this model have a relatively low average error compared to the first model. However, the model robustness must be tested with a couple of faulty measurements as inputs and monitor the divergence of the thermal performance from the expected values.

In both models, there is a 70 to 90 m3/hr from the actual value of volume flowrate; several factors contribute to such an error. Firstly, both models calculate the volume flowrate based on the energy balance around the customers' substation; the energy balance equation utilizes the values of density, specific heat capacity and customer supply temperature. Therefore, the temperature estimated by the two models had a calculation error cascaded to the volume flowrate calculation. Furthermore, the model doesn't consider the efficiency of the substation and therefore neglects any energy losses. Finally, the water properties are set to be fixed at different conditions, thus introducing some deviation from the actual flowrate.

5.4 Future Work

This thesis focused on simple modelling of the DH network and presented alternatives that could be easily set up and used without extensive prior knowledge. A possible future work would be to estimate the models' performance and suggest improvements when handling real-time data (the calculation step is one minute or less than a minute).

Furthermore, the future modelling could aim to capture the performance of the grid's components other than pipes, i.e., pumps and substations, and reflect their behaviour as a part of the system without introducing additional complexity to the modelling work. Moreover, this model could be integrated into DH optimization software to determine the possibility of optimizing the performance of the generation unit when coupled to the distribution network.

The model could also be customized and tested for different grid types, meshed and tree-structured. Introducing the actual grid geometry to complement the DH grid's model would provide much more insights into specific customers' areas and offer an in-depth analysis of the grid's performance at any particular segment.

6. Conclusion

In this thesis, two models were developed to capture the thermal and hydraulic behaviour of the district heating grid. The first research question was addressed by choosing the simulation modelling to present the dynamic behaviour of the grid performance, and four KPIs were selected to identify suitable approaches: accuracy, ease of use, robustness and resilience and data intensity. Two modelling approaches were selected: the district heating grid as a storage model and the delay analysis model. The models aimed to obtain the customers' supply temperature, the generation return temperature, the heat losses, and the volume flowrate. The simulation period was January of 2019.

The second research questions investigated the modelling performance against reality. The two models generated relevant results that followed the trend of the actual grid performance; the delay analysis model identified a heatwave delay of 2.17 hours in the supply pipe and 1.957 hours in the return pipe between the supplier and customer. The model then estimated the customer supply temperature with an average absolute error of 3.048 ^{o}C, and the generation unit return temperature with an average absolute error of 0.6936 ^{o}C. On the other hand, the grid as storage estimated the same parameters with an average absolute error of 2.92 ^{o}C and 0.85 ^{o}C for the customer supply and the generation return temperatures. Furthermore, both models estimated the grid's heat losses between 3 to 4% of the produced heat at the generation unit. The models were also able to calculate and identify the pattern of the grid's volume flow rate; the first model had an average absolute error of 87 m^3/hr, while the second model's average absolute error was 98 m^3/hr.

Lastly, the third research question aimed to introduce the potential application of the grid's models. The models provided insights about the grid behaviour; how the supply temperature and volume flowrate perform at different levels of customers' energy demand. The presented results also illustrate how the generation units control the energy output on different occasions by controlling these two parameters. Such results enable the generation unit to identify optimization potential and perform an optimization process regarding the grid's operation.

The models aimed to estimate the potential of using the grid storage capacity for flexibility provision by calculating the supplied energy in response to the change in forecasted energy demand. However, such an approach should be complemented with electricity prices to confirm the possibility of using grid storage.

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Appendices

Appendix A: delay analysis Model

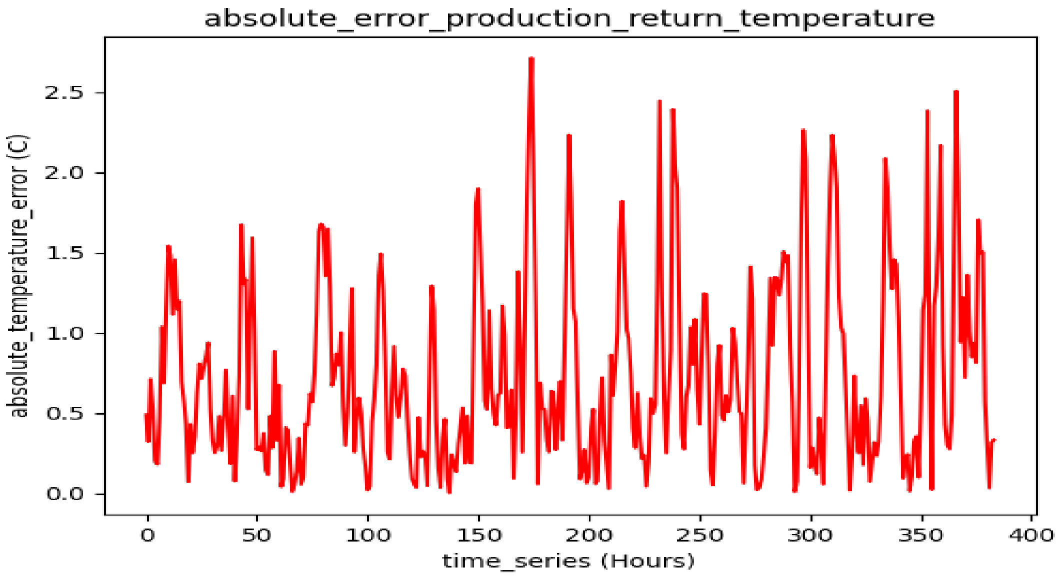

Figure 27 Absolute error of generation return temperature

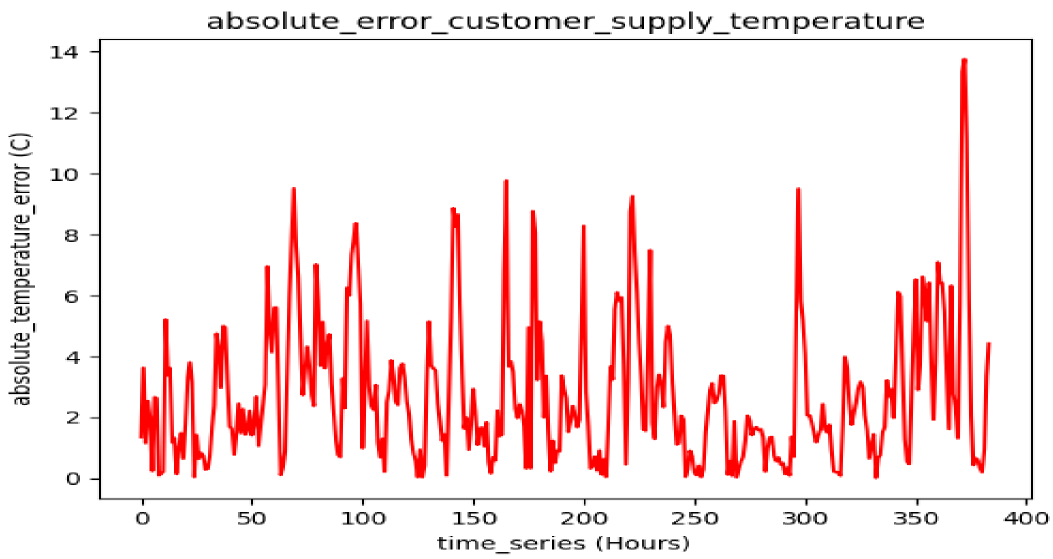

Figure 28 Absolute error of customer supply temperature

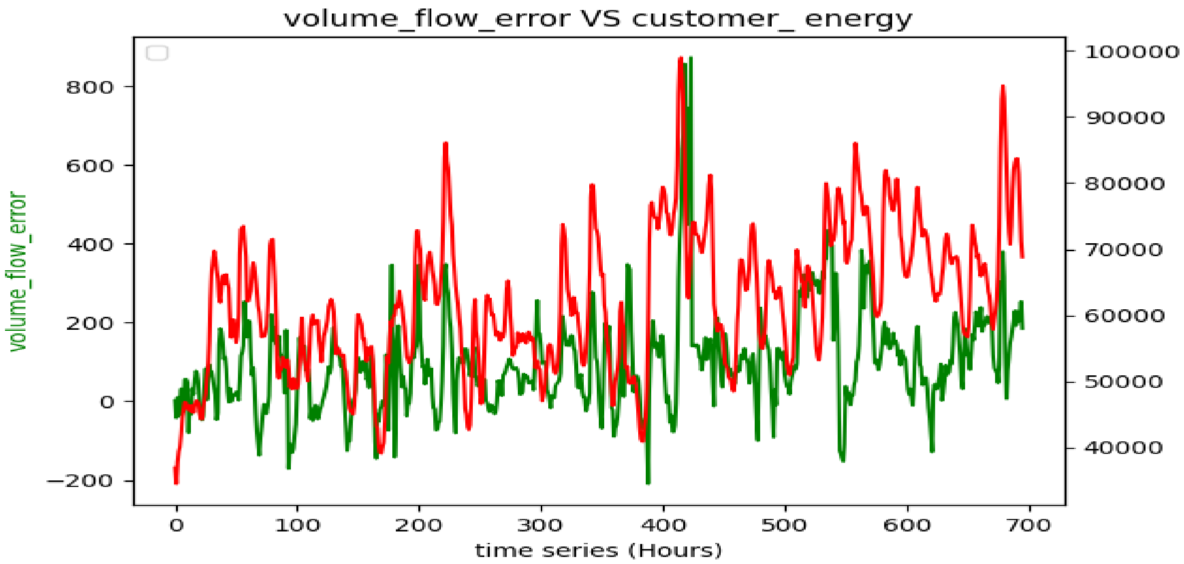

Figure 29 Volume flowrate error vs Energy demand

Appendix B: Grid as storage model

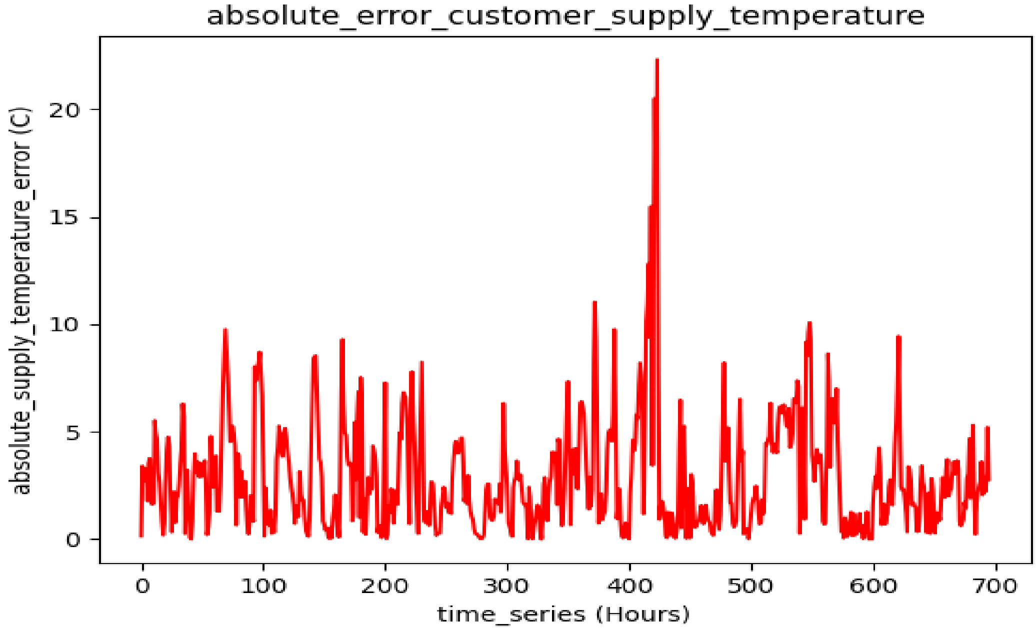

Figure 30 absolute error of customer supply temperature

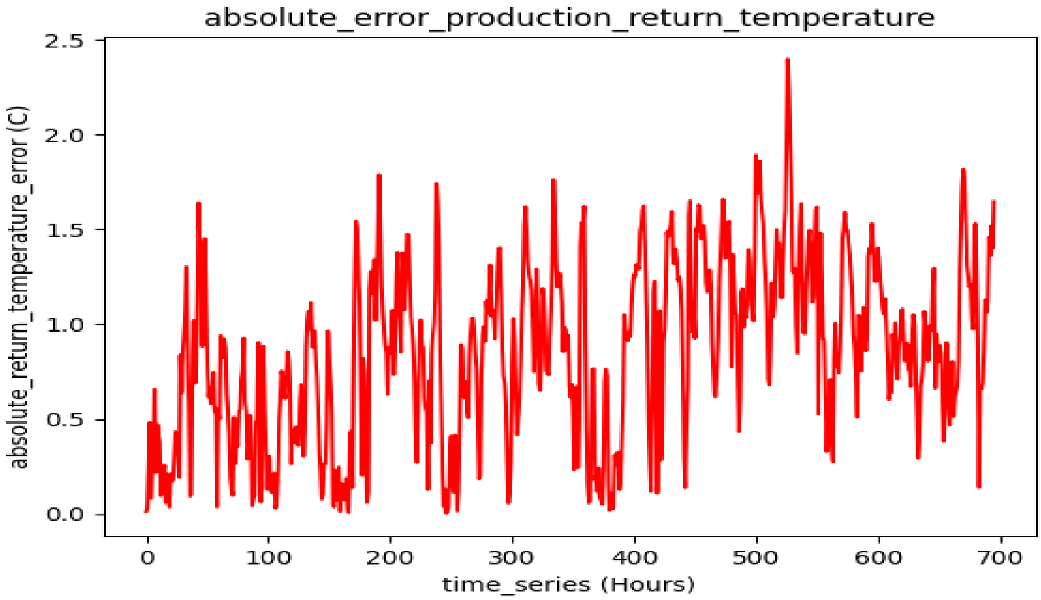

Figure 31 absolute error of generation return temperature

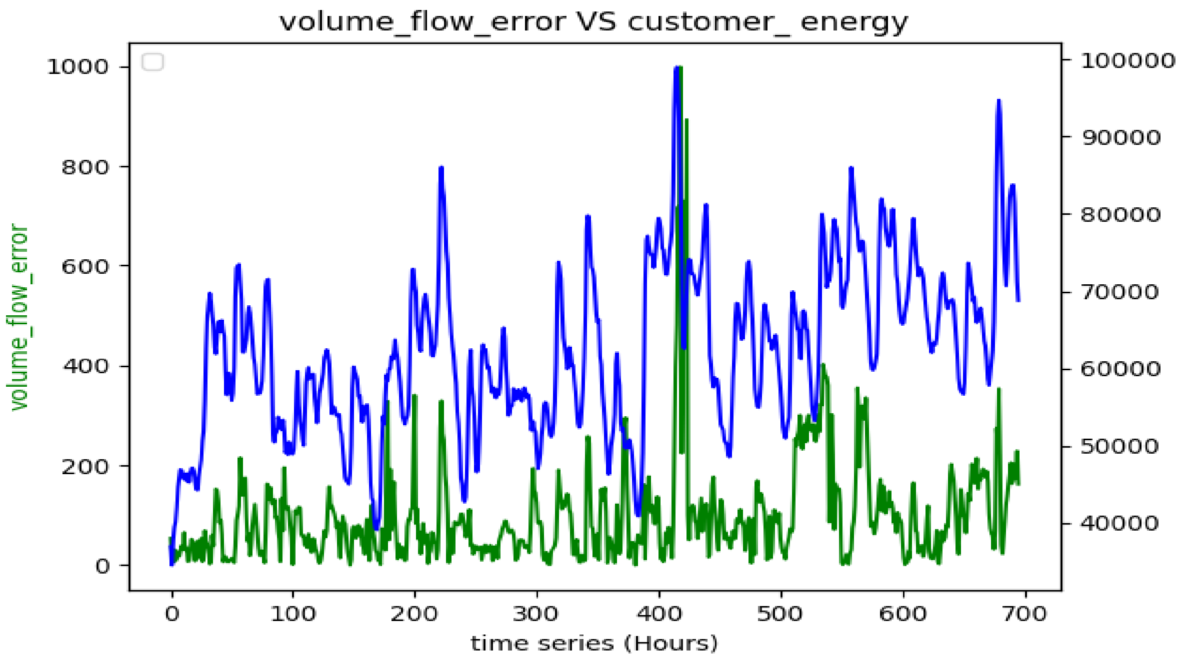

Figure 32 Volume flowrate vs demand energy

Appendix 3: Models comparison

Season	Parameter	Delay Analysis	Grid as storage
Winter	Average supply Temp. error	3.05	2.92
	Average return Temp. error	0.69	0.84
	Average volume flowrate deviation	78.97	98
	Average estimated grid's losses	2.6%	2.7%

Season	Parameter	Delay Analysis	Grid as storage
Spring	Average supply Temp. error	5.2	5
	Average return Temp. error	2.2	1.56
	Average volume flowrate deviation	75	56.58
	Average estimated grid's losses	17.7%	6.6%

Season	Parameter	Delay Analysis	Grid as storage
Summer	Average supply Temp. error	6.34	10.7
	Average return Temp. error	5.7	5.3
	Average volume flowrate deviation	93.48	69.15
	Average estimated grid's losses	40%	15.4%

Season	Parameter	Delay Analysis	Grid as storage
Autumn	Average supply Temp. error	4.7	5.2
	Average return Temp. error	2.4	1.7
	Average volume flowrate deviation	74.43	43
	Average estimated grid's losses	20%	10.8%

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