

Master thesis

Modelling of a District Heating System with Decentralized Heat Generators

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Abstract

In recent years, concern for the environment has been steadily growing and it is becoming more common to investigate methods in dealing with low carbon heat or electricity generation.

Solar collectors and, in particular systems integrating solar collector units on roof tops or open ground surfaces coupled with cogeneration units, offers a significant potential for greenhouse gas reduction.

Environmental awareness increases, with demands for environmental certifications of new communities and buildings as a result. In the district heating industry, enabling of decentralized energy is one way to meet requirements from customers. In this thesis the modelling of small-scale local solar-collectors as heat generators on district heating distribution networks is investigated. Customers in this way can both produce and consume heating are in this thesis called “Prosumers”. The modelling and the study have mainly been performed through simulations in the computer programme Simulink. The hydraulic aspects of the district heating network are modelled using the Customised blocks in Simscape. The thermodynamic aspects of the district heating network are modelled using CARNOT Blockset in Simulink (**C**onventional **A**nd **R**enewable **e**Nergy systems **O**pTimization Blockset). The bidirectionality of the transfer of data between the physical and CARNOT components are dealt with customised blocks modelled in Simscape language. Building a district heating network using the components, testing simulation run time, function and investigation with heat generators (concept of decentralized heat generators) stands out to be the main part of this thesis.

MODELLING OF A DISTRICT HEATING SYSTEM WITH DECENTRALIZED HEAT GENERATORS

Declaration

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I hereby declare that the Master Thesis submitted with the title

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is my own unaided work. All direct or indirect sources used are acknowledged as references.

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I agree to the further use of my work and its results (including produced methods and models) for research and education.

This paper was not previously presented to another examination board and has not been published.

Munich, 17.12.2015

.....
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Chapter 1. Introduction

1.1 Background

This section reviews the concept of district energy, its opportunities and challenges, and the context in which it is best used.

1.1.1 District Heating Systems

At its most basic level district energy is defined as an approach to energy provision „*in which heat is produced centrally and hot water is piped to the buildings*“. [1] In fact, district energy can provide heating for space heating and hot water or chilled water for air conditioning. District energy systems generally consist of three sub-systems which are:

- the collection and/or generation of thermal energy
- the distribution of the thermal energy from plant sites to a network of energy consumers
- the transfer of the thermal energy to the energy consumer. [2]

„*A district can consist of a small neighbourhood or a large part of a community*“. [3]

For district heating, what is understood is a centralized heating system for a neighbourhood, town, city and so on. Instead of having individual boilers at each house, district heating systems deliver hot water to all the consumers for hot tap water, heating systems or industrial processes.

The water is heated in one or more heating plants and then is transported along the entire network to the end users. This hot water is around 70 °C and 120 °C depending on the weather conditions. Each customer has a substation, where the heat is delivered with a heat exchanger. The water is brought back again to the heating plant, where it is heated again. This first closed circuit is called the *primary circuit*, and its function is to transport the heat from the plant to the customer substations with minimum losses. The pipes used in the primary circuit are well insulated in order to minimize heat losses to the environment.

The customer substations depend on the consumption of hot water of the consumer. For residential buildings, the most typical scheme is shown in Figure 1. In this figure, it can be seen how the hot water coming from the network heats the water required for hot tap water on one side, and hot water for the radiators for space heating on the other side. These transfers are done through two heat exchangers, one for each purpose. Water streams in these heat exchangers are determined by the heating requirements, i.e. the more heat required, the more water flows through it. In the case of industrial purposes, the substation will depend on the needs of the customer.

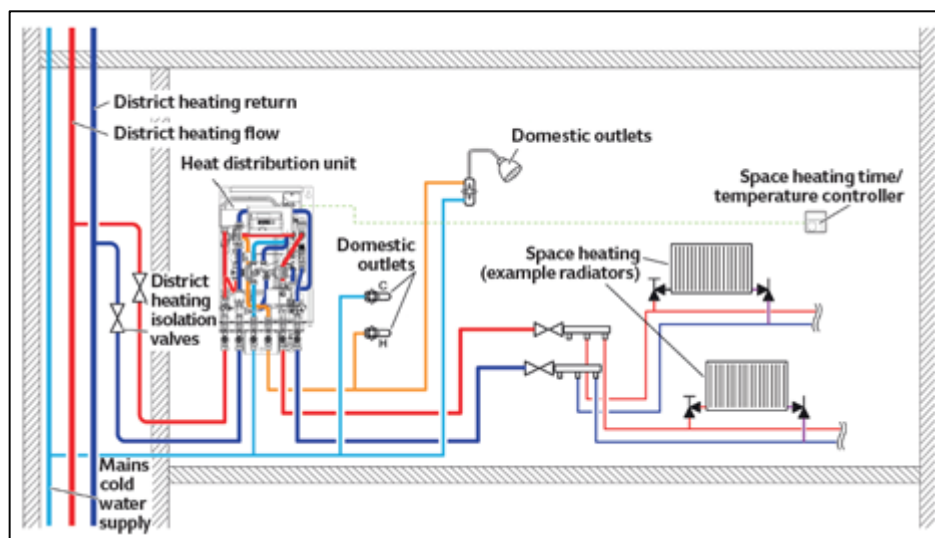


Figure 1: Example of distribution of heat to individual consumer from heat network
(Source: Based on Bosch Commercial and Heating Illustration)

The company in charge of the network is able to monitor the amount of energy that is transferred at any substation, and depending on this transfer the company will bill the consumer. There are several fees on the district heating bills, and they are not always the same in all networks. The most typical fees are related with the energy transferred during a period of time (for example a month) and the maximum power that the consumer could use. These two fees are so common and they are known in the bills for electrical energy. There are networks that also include a fee for the volumetric flow consumption. It means that if the consumer consumes a lot of heat, he or she will have to pay the amount of energy used but also a high fee for the flow.

District heating has many advantages. The combustion to heat the water is only done in one place. It means that it is easier to study it and improve its efficiency. There is only one chimney, not like an individualized system where each boiler has its own chimney. So the exhaust gases can be treated, and it results in a cleaner atmosphere. In addition, heating plants can use different kind of fuels, such as coal, natural gas or oil but also some renewable sources like biomass. There are also plants that get the heat burning waste, so they use energy that otherwise would be lost. Some of the power plants produce both electricity and heat, so the global performance is very high. All these characteristics usually results in a more environmental friendly system than the conventional one. Finally the customers have also some advantages, given that they do not have to invest in any boiler or furnace [Svensk Fjärrvärme, 2009].

Some networks have also pipes for distributed cold water to supply cold instead of heat. This technology is called *District Cooling*. It works in the same way as district heating, but with chilled water. These networks can be very useful in countries with warm climates.

1.1.2 District Heating in Germany

In Germany district heating has a market share of around 14% in the residential buildings sector. The connected heat load is around 52.729 MW. The heat comes mainly from cogeneration plants (83%). Heat-only boilers supply 16% and 1% is surplus heat from industry. The cogeneration plants use natural gas (42%), coal (39%), lignite (12%) and waste/others (7%) as fuel. [4]

The largest district heating network is located in Berlin whereas the highest diffusion of district heating occurs in Flensburg with around 90% market share. In Munich about 70% of the electricity produced comes from district heating plants. [5]

District heating has rather little legal framework in Germany. There is no law on it as most of district heating are regulated in governmental or regional orders. There is no governmental support for district heating networks but a law to support cogeneration plants. [6]

1.1.3 Decentralized Heat Generators in District Heating Network

1.1.3.1 New technological options for heating

As new Renewable Energy (RE) technologies are developed, additional technical options for increasing the shares of RE in DH system are presented. Fuel switching and co-firing of biomass in existing fossil fuel-fired heat-only or CHP boilers present an option in the near term. The suitability of biomass fuels, their moisture contents, and the need to be pulverized or not, depend on the existing boiler design (whether grate, circulating or bubbling fluidized bed). [7]

Heat from geothermal and solar thermal sources can be more readily integrated into existing DH systems. Enhanced geothermal systems (EGS) could be operated in CHP mode coupled with DH networks. The commercial exploitation of large heat flows is necessary to compensate for the high drilling costs of these deep geothermal systems. Such a large heat demand is usually only available through DH networks or to supply major industries directly. [7]

1.1.3.2 Storage options

Heat storage systems can bridge the gap between variable and unsynchronized heat supply and demand. The capacity of a thermal storage can range from a few MJ up to a several TJ; the storage time from hours to months; and the temperature from 20 °C up to 1,000 °C. These wide ranges are made possible by choosing between solids, water, oil or salt as different thermal storage materials together with their corresponding storage mechanisms.

A hot water storage system design depends on the local geological and hydro-geological conditions, the supply and demand characteristics of the DH system. For short-term storage (hours and day) the thermal capacity of the distribution system itself can act as storage (Figure 2). Longer-term storage, usually between winter and summer, is less common. In this case, the main storage options include underground tanks, pits, boreholes and aquifers (Heidemann and Müller-Steinhagen, 2006). Seasonal storage is likely to become more important where high shares of solar thermal energy are used in DH systems due to the seasonal and daily variability of the solar resource. In order to integrate large-scale solar systems in DH networks, the development of the

systems for seasonal heat storage (Figure 2) has made progress and several demonstration plants have been realized (Bauer et al, 2010). [7]

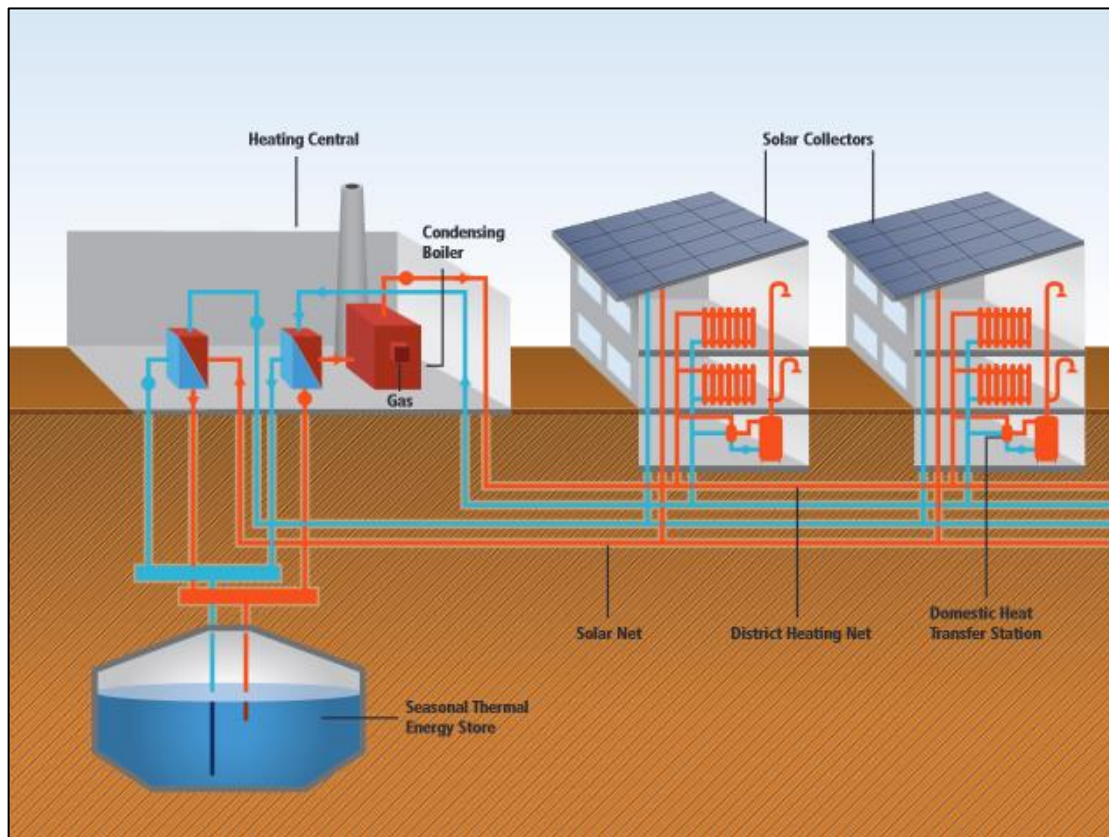


Figure 2: Solar-supported centralized heating plant with seasonal tank storage connected to a district heating system (modified from Bodmann et al, 2005) [15]

1.2 Literature Study

There are many existing and future energy demands for low temperature heat that are currently being satisfied by employing combustion of fossil fuels, providing high temperature heat. Similarly, the use of electricity for these heat loads means using a high-quality energy source for low-quality heat demand. It is therefore preferable to use the difference between the high temperature heat and the low temperature to generate electricity. However, this is not generally feasible without a centralized system like district energy facilitating the capture of additional and significant energies (Rogner, 1993). The improved efficiencies translate into economic benefits and reduced pollution. Further, district heating helps overcome three barriers to the wider dissemination of renewable energy, namely:

- Periodic fluctuations associated with the generation
- The low energy density of renewable energy carriers relative to fossil fuels
- The limited utilization of renewable energy by consumers, including provision, conversion, storage, transport and use (Stremke & Koh, 2011).

In its synopsis of an upcoming report on district energy, the United Nations Environment Program (UNEP) identified the following policy goals that cities hoped to achieve in applying district energy [8]:

- **Reduce greenhouse gas emissions:** Achieve rapid, deep and cost-effective emissions reductions, with reduction of primary energy consumption by 30-45 per cent.
- **Improve air quality:** Address indoor and outdoor air pollution and their associated health impacts, by reducing coal and oil consumption.
- **Improve energy efficiency:** Achieve operational efficiency gains of up to 90 per cent, by using district energy infrastructure to link the heat and electricity sectors.
- **Local and renewable resources:** Harness local energy sources, including from waste streams, reject heat, natural water bodies and renewable energy. Pilot new technologies, such as thermal storage, to integrate renewables.
- **Resilience and energy access:** Reduce import dependency and fossil fuel price volatility. Manage electricity demand and reduce the risk of brownouts.
- **Green economy:** Achieve savings from avoided or deferred investment in generation infrastructure and peak power capacity. Create wealth through reduced fossil fuel bills and generate local tax revenue. Create jobs for design, construction, operation and maintenance.

1.2.1 Modelling in Simscape

Simscape offers a MATLAB-based, object-oriented, physical modelling language for use in the Simulink environment. Simscape is a software extension for MathWorks Simulink and provides tools for modelling systems spanning mechanical, electrical, hydraulic and other physical domains as physical

networks. From these different physical domains it is possible to create models containing customised components. Simscape provides a set of block libraries and special simulation features especially for modelling physical systems that consist of real physical components. It is accessible as a library within the Simulink environment. [9]

Blocks in traditional modelling tools such as Simulink represent mathematical operators and when it is connected together a system of different mathematical operators with specific inputs and outputs is obtained. In Simscape each block in the system consists of functional elements that interact with each other by exchanging power or energy through their ports.

Connection ports in Simscape are bidirectional, where energy can flow in both directions. Connecting Simscape blocks represents connecting real physical components like shafts, valves, drive trains, etc. Flow direction does not have to be specified when connecting Simscape blocks into the network. [9]

1.2.2 Modelling in CARNOT

The CARNOT Blockset is an extension for MATLAB/ Simulink. It is a tool for the calculation and simulation of thermal components of heating systems with regards to conventional and regenerative elements.

The CARNOT Blockset is a set of two libraries of typical components of these systems. It is organized in blocksets like the Simulink library. The handling of the blocks is exactly as in Simulink, so that users familiar with Simulink can directly use the new blocksets in the same way.

Two libraries are included in the toolbox:

- The CARSYS library contains commercially available components of heating systems. It is intended for simulation, design and analysis of heating systems using standard components.
- The CARNOT library contains a wider range of elements which can be user-defined and some basic functions to facilitate the modelling. The CARNOT library was designed for more sophisticated simulation and analysis of heating systems. [10]

Furthermore, components for real-time-workshop models are included. The real-time-workshop enables real-time simulation and the creation of stand-alone

programs directly from the Simulink Model for different target platforms, offering a wide range of applications. [10]

1.2.3 Integration of Solar Thermal Systems into District Heating Networks

The development of solar district heating is gaining more and more interest, but, in some case the space available for the integration of solar collectors on the ground is limited and the use of decentralized systems is necessary. [11]

Solar district heating is becoming more and more popular in European countries especially in Denmark where dozens of systems are already installed since many decades. [12]

In France, the interest for solar district heating is new, but is growing quickly, especially with the development of new districts with low-energy buildings. In such context, solar thermal energy can achieve significant fractional energy savings for both space heating and domestic hot water preparation. As these areas are densely populated, solar collectors cannot be implemented on the ground, but should be installed on the roof of the buildings. Such implementation offers many options for hydraulic connection of the solar collectors to the district heating network as well as for the implementation of thermal energy storage. [11]

1.2.3.1 Decentralized solar district heating systems

In decentralized solar district heating plants the solar collector fields are installed at suitable locations at any place of the district heating network and connected directly to the district heating primary circuit on site. Often these plants utilise the district heating network as storage (as long as they provide a minor amount of heat in comparison to the total load in the district heating system). [13]

Systems realised so far are owned and managed either by a housing company or by an energy service or by the district heat supplier. [13]

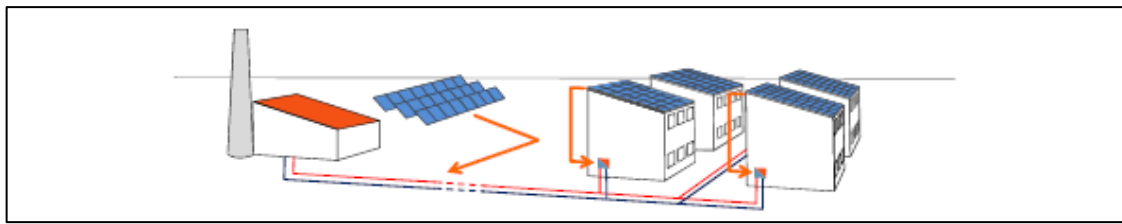


Figure 3: Decentralized solar district heating system (Source: Solites)

1.2.3.2 Position in the heating grid

If the position of the solar thermal plant is decentral, thorough analysis of the district heating (DH) grid has to be performed in advance. „Decentral“ means that the solar thermal plant is not closely located to another major heat generator like a biomass or fossil fuel fired plant. A central feed-in point can also be a transfer station from a connection line to a remote power or heat plant. [14]

1.2.3.3 Feed in principles

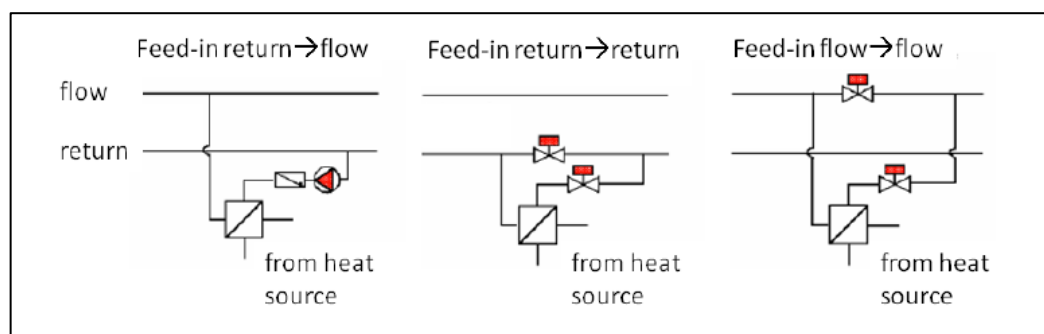


Figure 4: Hydraulic integration of solar thermal feed-in (Source: Streicher)

➤ Feed-in return-> flow

As this feed-in mode, the required temperature hub in the heat generator is defined by flow and return temperatures of the heating grid. The solar plant has to be operated at matched flow volumes, adjusted to the required flow temperature. The feed-in pump has to overcome the pressure difference between return and flow. This temperature difference is at several bar quite high compared to the pressure loss of the collectors and pipes (several 100mbar). Heating grid operators prefer this feed-in principle, as there is no

change in return temperatures and part of the pump cost has to be beared by the feed-in operator.

➤ **Feed-in return-> return**

Here operating temperature of the solar plant is lowest compared to other feed-in modes. Thus highest solar yields can be expected. No pumping energy is required at feed-in point as pressure loss of pipes and heat exchangers is covered by grid pumps. Mass flow in the collector circuit can be constant. Return-return-feed-in is not favourable for heating grid operators as they have to install a low resistance in the grid pipe for control of the flow in the heat exchanger for feed-in. Additionally high return temperatures are not favourable for most heating grid opeartors as heat losses rise and the efficiency of other heat generators tends to decrease.

➤ **Feed-in flow-> flow**

This feed-in mode results in high collector temperatures and low efficiencies of the solar plant. Here also the grid operator has to install a flow resistance in the grid pipe for control of the flow in the heat exchanger for feed-in. Due to low efficiency, this principle is normally not in use.

1.2.4 Design Temperatures in a District Heating Network

In this chapter, the temperature levels in a district heating network will be explained. These temperatures will be chosen for discussing their impact and consequences. Later the effects that the customer has in the temperatures of the network will be described. Finally, some measures are detailed in order to decrease the return temperature in the network.

1.2.4.1 a The Choice of Design Temperatures

The choice of design temperatures is both a complex and a very important step in the design of a DH network. Operational temperatures in the network affect the delivery capacity of heat, the heat losses, the pumping power needed to

transport the water, and finally the effect it has on the net electricity production of Combined Heat and Power (CHP) and the heat produced in heat pumps. Therefore it is also essential to optimise the district heating temperatures that has been developed since DH exists.

There are two different temperatures, the *supply temperature* and the *return temperature*. The first one is the hot temperature of the water that comes from the central heating plant and goes to the consumer substation. This temperature is determined by the production plant. The second one is the temperature of the water after this substation, so it is a lower temperature. Return temperature is not an operational parameter; it is a result of effective operation in practice, so it is influenced by the consumers and the topology of the network [15].

The effects of changes in these two temperatures will be described in the next subchapters from a general point of view.

1.2.4.1 b Influence on delivery capacity of heat

In the district heating networks, there are two parameters to control the heat energy delivered to the consumer. The next equation (Eq.1.1) shows that the power a consumer receives (P) in the substation depends on the temperature difference between hot supply and cold return water (ΔT), the mass flow (\dot{m}) and finally the specific heat capacity (C_p):

$$P = \dot{m} C_p \Delta T \quad (\text{Eq.1.1})$$

$$\Delta T = T_{\text{supply}} - T_{\text{return}} \quad (\text{Eq.1.2})$$

C_p is an intensive property that depends on the fluid (for water $C_p = 4.18 \text{ KJ/kg.K}$ at standard conditions, but it varies with the temperature). For this reason it is not a parameter that can be used to change the power delivered to the consumers, only the temperature and the mass flow can be used for this purpose. Since T_{return} is not determined by the central heating plant, only T_{supply} and the mass flow can be changed by the supplier. These two parameters are the tools to adjust production to the demand at any moment along all days of the year.

With the equation represented (Eq.1.1) it is shown that the total power delivered is proportional to the temperature difference in the medium. It means that any decrease of T_{supply} or otherwise any increase of T_{return} has a decreasing effect

on the total power transported. An effective district heating network has two characteristics: a low supply temperature and a high temperature difference between supply and return. A low supply temperature increases the efficiency of the production and decreases the transport heat losses. On the other hand, a high temperature difference (ΔT) results in a mass flow reduction, i.e. pumping energy savings.

Hence there is a need of reducing T_{supply} and increasing ΔT . Since the energy transported is proportional to ΔT , an efficient network should have a low T_{return} . As stated before in the same chapter, return temperature is not an operational parameter because it depends on the consumer's part of the network. Nevertheless, the effort to have efficient networks is resulting nowadays in improvements in the consumer's substations, reduction of malfunctions in the substations and their connection to the network.

Large nets in Sweden use 120 °C as the basic design temperature. In other countries it can be different. In Germany it is around 130 °C and in the East of Europe it can be even 150 °C.

Return temperature depends mostly on the house heating systems. The old systems are designed to work with supply temperatures of 80 °C and return of 60 °C, whereas the modern ones use 60 / 45 °C. The combination of these two technologies could result in effective heating system temperatures of 70 / 50 °C. [15]

1.2.4.1 c Influence on the pumping work

The pumping work is the energy needed to transport the hot water from the production plant to the consumer's and then bring it back again to the plant. For this purpose some pumps are installed along the network, usually most of them at the heating plants. For decentralized networks, installation of the pumps at the decentralized substation is essential. The pressure drop is measured far away from the plant and if the pressure is not high enough, the pump is ordered to deliver a higher one. [15]

These pumps have to deliver the pressure that is lost along the supply and the return pipes owing to friction between the water and the pipes. The friction does not have a linear relation with the mass flow, but is roughly proportional to the

third power of the flow rate. It means that a decrease in the water flow has a large impact on the power consumption for pumping. [15]

Looking again at equation *Eq.1.1* it can be seen that for a given power delivered, an increase of the temperature difference results in a decreased mass flow and, consequently, in a reduction of the pumping work and costs.

Concluding, it can be seen again that increasing the temperature difference has a very positive impact on the energy savings, in this case, on electrical energy.

1.2.4.1 d Influence on the heat losses

The heat losses in a district heating network are proportional to the temperature difference between the ambient and the fluid in the pipes. Since ambient temperature is not an operational parameter, the heat losses depend on the supply and return temperatures of the net and its mass flow. For an existing district heating network, with all the distribution pipes and their insulation installed, only the temperature levels and the flow can be changed in order to decrease the heat losses of distribution.

The next energy balance equation shows the energy supplied to the consumer:

$$\dot{Q}_{plant} + \dot{W}_{pump} = \dot{Q}_{loss} + \dot{Q}_{cons} \quad (Eq. 1.3)$$

Where \dot{Q}_{plant} is the heat produced in the production plant, \dot{W}_{pump} is the work transferred by the pumping stations, \dot{Q}_{loss} is the heat loss along the network, and finally \dot{Q}_{cons} is the heat supplied to the consumer substation.

The typical model for the heat losses per unit length (\dot{Q}_{loss}) can be obtained with the next expression:

$$\dot{Q}_{loss} = 2 \cdot \left(\frac{T_{pipes} - T_{out}}{R_{ins} + R_{hole} + R_{channel} + R_{soil}} \right) \quad (Eq.1.4)$$

Where T_{pipes} is an average temperature of the two pipes (supply and return pipes):

$$T_{pipes} = \frac{T_{supply} - T_{return}}{2} \quad (Eq.1.5)$$

The losses are multiplied by 2, because of the two pipes, one for supply and the other for return water. The thermal resistances of the insulation in the pipes (R_{ins}), the channel hole (R_{hole}), the channel ($R_{channel}$) and the soil (R_{soil}) are

calculated depending on the shape and on the materials, and taking into account the mass flow.

For this reason it is important to take into consideration the heat losses when determining the optimal design temperatures in a DH network. It must be known that normal values of heat losses in district heating network are higher than 10% of the energy supplied. [15]

The optimization of the heat losses is reducing both supply and return temperatures to a minimum. In fact, it is true that this measure would reduce the heat losses. Other consequences must be considered, such as the fact that decreasing the temperature difference would result in a higher mass flow and, therefore, a higher pressure drop and higher energy consumption for pumping. Furthermore, it is not possible to decrease supply temperatures below the requirements of the consumers.

1.2.4.2 Conclusion

The efficiency of a district heating network is primarily dependant on the temperature levels. Hence, it is important to optimize both supply and return temperatures. This optimization results in lower energy consumption, a required and well known aim of nowadays.

A proper optimization must take into account all the effects described along this chapter and their interaction. It must be known that sometimes the improvement of one of these effects results in a worsening of the others. For this reason, in optimizing the whole network, the production, the transmission, and the consumer substations must be studied.

1.3 Motivation

When developing a district heating network either for better and energy efficient performance or to be used in a future district heating network with different decentralized heat generators, the new functionality has to be verified. Performing verifications and tests in a real district heating network is expensive. It is not only necessary to have a district heating network with test and measurement equipment, also some kind of climate chambers are essential where it is possible to control the surrounding climate along with the flow and

return flow temperatures of the district heating network. These are parameters that significantly affect the temperature and pressure losses in the network.

To overcome the need of a real district heating network and test environment there is a desire to construct a model representing the temperature and pressure losses along the district heating network, using mass flow rate and temperature sources as inputs. In a mathematical model the user needs to set up all the equations of the system in order to simulate it, but in a physical model components, e.g. pipes and pumps or flow rate sources, are put together and the modelling tool automatically analyze and solve the equations that constitutes the system. Compared to a mathematical model, a physical model is more intuitive and easier to understand. In a physical model it is also easier to see what is missing and to add and test new or different conditions, e.g. the impact of radiation.

1.4 Goal

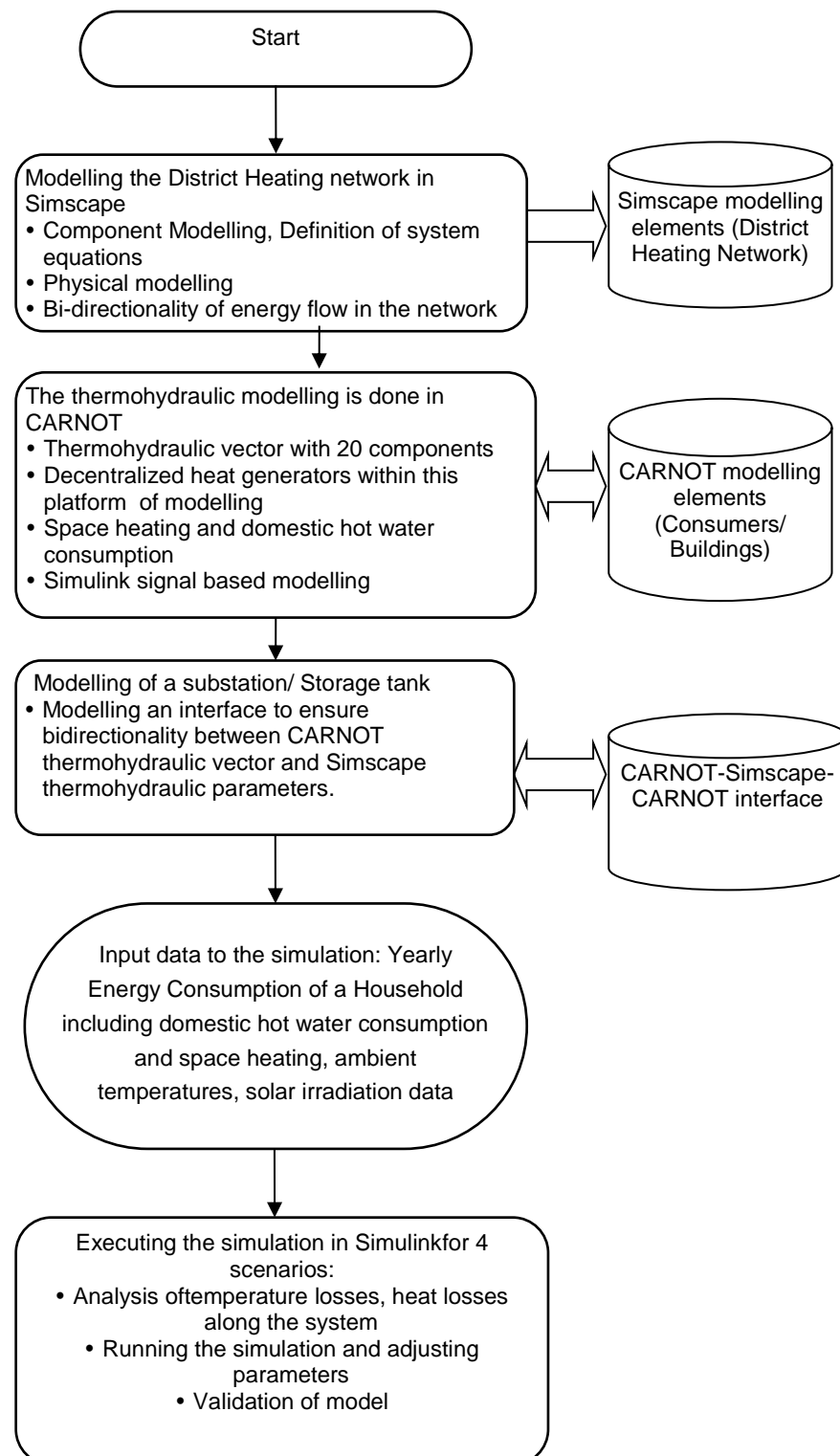
- To get an understanding of how to model with Simscape and CARNOT simulation software.
- To model a district heating network with decentralized heat generators in the Simscape environment by means of physical and mathematical relationships and technical data.
- Research about Simscape's modelling potential in respect to usability, compilation/ troubleshooting and simulation ability.
- A bi-directionality of information flow between CARNOT and Simscape components used in building the model.
- The secondary goals are to investigate the temperature and pressure losses in a district heating network with a model based on a physical insight. This involves testing control strategies in a district heating network which primarily consists of influencing the feed of decentralized heat generation in the network based on supply and return temperatures in the network.
- The influence of different heat generators is a secondary goal as part of the thesis.

1.5 Method

The work method can be described by the following steps:

1. At first theories and fundamentals of district heating networks are studied, especially the temperature and pressure losses along the network.
2. The use of decentralized heat generators is part of the initial phase.
3. The second step is to learn working with Simscape, both the basics of physical modelling in Simscape and the parts related to thermal and hydraulic models.
4. To investigate thermohydraulic aspects of the model mainly in the generator and the consumer side of the district heating network, CARNOT is used.
5. The individual tests of the CARNOT (Simulink signal) models and the Simscape (physical signal) models are then integrated to create the district heating network.
6. Finally the DH network model is constructed, tuned and then optimized regarding modelling effort, stability and simulation time.

1.6 Outline



Chapter 2. Modelling Methods

2.1 Modelling in Simscape

Simscape is a physical modelling tool delivered by MathWorks as a toolbox to Simulink. For more information, see [16]. The first release, version 1.0, came according to [16] together with Matlab R2007a. The Simscape file is a dedicated file type in the MATLAB environment. It has the extension .ssc.

The Simscape file contains language constructs that do not exist in MATLAB. They are specific to modelling physical objects. However, Simscape file incorporates the basic MATLAB programming syntax at the lowest level.

2.1.1 Physical Modelling - Simscape

Physical modelling is a way of modelling and simulating systems that consist of real physical components. It employs a physical network approach, where Simscape blocks correspond to physical elements, such as pumps, motors. Joining the blocks corresponds to the physical connections that transmit power. This approach lets one describe the physical structure of a system, rather than the underlying mathematics.

Simscape Foundation libraries contain a comprehensive set of basic elements and building blocks, organized by domain. Connecting these blocks together would ensure assembling a physical system. Using these blocks, along with the blocks from the add-on products, such as SimElectronics® or SimDriveline™, ensuring one to model multidomain physical systems. [17]

Simscape as mentioned before, also a physical modelling tool, but is delivered by MathWorks as a toolbox to Simulink. This gives the advantage that Simscape models can be integrated with Matlab, Simulink and other products of MathWorks. In Simscape, the Simscape programming language is used to define custom components, see [18]. As stated in [19], the Simscape programming language is based on MATLAB object oriented language, in order to be able to integrate it with the Simulink environment, not only when it comes to physical components, but also areas of physics. The later refers to Simscape's domains, covered in later chapters.

2.1.2 Differences between Simulink and Simscape Modelling

In this section, at first, the big differences between Simscape and Simulink modelling will be explained. Then some of the properties that are special for Simscape are presented. Here „Simulink“ mainly refers to the basic Simulink library.

There are some distinct differences between Simulink and Simscape and they are as follows. Further information can be found in [20] and [21]:

1. In Simulink mathematical operations are modeled, but in Simscape the model is constructed by blocks representing physical components and physical relationships between them. It can also be said that in Simulink the model is constructed by defining equations for the system, but in Simscape the physical system with components is constructed and Simscape analyzes and solves the equations that constitutes the system.
2. The connections in Simulink are unitless and any block can be connected to any other block, even if the simulation shows unlikely results. In Simscape the connections represent physical connections between components and can have units. For example a voltage source can be connected to a diode, but Simscape does not allow to connect a mass flow source to a diode.
3. The connections in Simscape are bidirectional. It means for example, the mass flow can be in a positive or negative direction, depending on the pressure difference in the system. Compared to Simulink where all connections are unidirectional.

2.2 Code

The Simscape language is used to define and create components in Simscape, defining nodes, ports, parameters, variables and the equations. See chapter 2.3 for more information.

2.2.1 Basic File Structure

A model may be a domain or a component model. Each Simscape file starts with a line specifying the model class and identifier.

ModelClass Identifier

Where

- *ModelClass* is either a domain or component
- *Identifier* is the name of the model

For example:

domain rotational Or

component spring

The basic file structure for domain models and component models is similar.

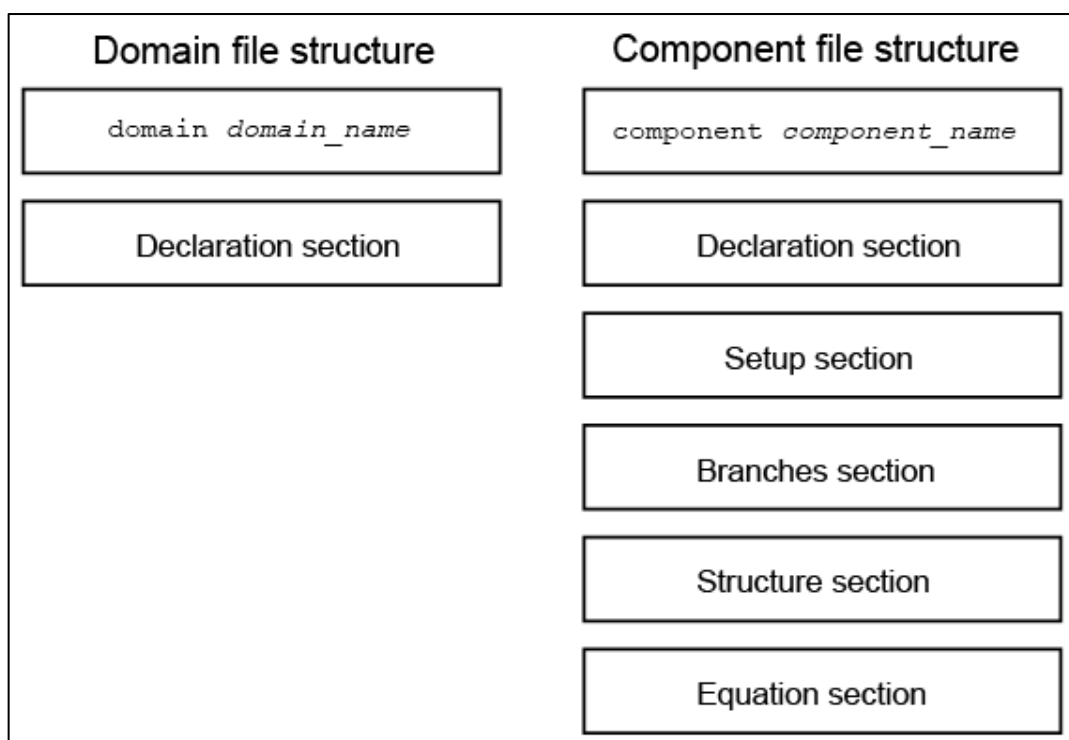


Figure 5: Basic File Structure for domain models and component models- Simscape [17]

A Simscape file splits the model description into the following pieces:

- *Interface or Declaration* – Declarative section similar to the MATLAB class system declarations:
 - For domain models, declares variables (Across and Through) and parameters. (See Chapter 2.2.2)
 - For component models, declares nodes, inputs and outputs, parameters, and variables. (See Chapter 2.2.4)

- *Implementation* (only for component models) – Describes run-time functionality of the model. Implementation consists of the following sections:
 - *Setup* – Performs initialization and setup. Executed once for each instance of the component in the top-level model during model compilation.
 - *Structure* – For composite components, describes how the constituent components ports are connected to one another and to the external inputs, outputs and nodes of the top-level component. Executed once for each instance of the component in the top-level model during model compilation.
 - *Equation* – For behavioural components, describes underlying equations. Executed throughout simulation [22].

2.2.2 Through and Across Variables

In the physical network there are two variable types and they can be described in the following way:

- *Through variables* – as stated in [21], „Variables that are measured with a gauge connected in series to an element“.
- *Across variables* – as stated in [21], „ Variables that are measured with a gauge connected in paralalled to an element“.

2.2.3 Physical Domains

A physical domain creates an environment in which the physical network connects components and it is mainly defined by across and through variables. Simscape Language Guide gives helpful information about Simscape’s physical domains. Figure 6 shows an example of how the Electrical domain is defined with voltage as across variable and current as through variable. The parameters can be used by components that belong to the domain.

The electrical domain declaration is shown below.

```
domain electrical
% Electrical Domain

% Copyright 2005-2013 The MathWorks, Inc.

parameters
    Temperature = { 300.15 , 'K'      }; % Circuit temperature
    GMIN         = { 1e-12 , '1/Ohm' }; % Minimum conductance, GMIN
end

variables
    v = { 0 , 'V' };
end

variables(Balancing = true)
    i = { 0 , 'A' };
end

end
```

Figure 6: The Electrical domain where current (i) is through variable, defined by the (Balancing = true) parenthesis.

In the software release of Simscape (2015a) there are a number of domains included such as the electrical, mechanical, rotational, pneumatic, thermal, thermal liquid, magnetic. To create a thermohydraulic model with pipes and pumps, the thermal and hydraulic domains are convenient to use. Their through and across variables are presented in Table 1.

Table 1: Across and through variables in the domain

Domain	Across variable	Through variable
Thermal	Temperature (K)	Heat flow (J/s)
Hydraulic	Pressure (Pa)	Flow rate (m ³ /s)

If the domains following Simscape are not enough, it is possible to create a new domain and components belonging to it. The drawback is that the components can only be connected to other components in the same domain.

2.2.4 Components

To learn how a new component is created, see chapter 2.3.

The components in Simscape are, alike Simulink with blocks and the Simscape block can have the following two kinds of ports.

- *Physical Conserving ports* are the physical connection ports. They can for example be thermal or hydraulic. For physical conserving ports it holds that:
 - The connections between them are bi-directional.
 - Each physical conserving port belongs to a domain and they can only be connected to other physical conserving ports of the same domain.
 - The connection lines between them carry variables, across and through variables.
 - Two conserving ports that are directly connected to each other must have the same value on the across variable, e.g. angular velocity.
 - The connection lines from a physical conserving port can be branched into several connections and the following happen with the through and across variables:
 - The components directly connected to each other must have the same value on their across variables.
 - The value of the through variables are divided among the connections in the branch and the sum of the incoming through variables is equal to the sum of the outgoing ones.
- *Physical Signal ports* carry signals between blocks and their connections are more alike the connections in Simulink, but using Simulink ports would slow down the computation speed. For the physical signal port that it holds:
 - It can be connected to each other, bringing physical signals between Simscape blocks.
 - The signals connecting them can have units, but only one unit per signal.

- It can be connected to regular Simulink blocks using the Simulink-PS and PS-Simulink Converters.

2.2.4.1 Connecting Physical Signals to Regular Simulink Components

The physical signals can be converted to regular unitless Simulink ports through a converter. There is one converter for each direction, one for converting a physical signal to Simulink and one for converting a Simulink signal to a physical signal. In both cases the unit of the physical signal can be specified in the block dialog boxes. The conversion to and from Simulink is especially useful when using data as input from and output to the workspace.

2.3 Creating a Custom Component in Simscape

The domains in Simscape include several different components for construction of physical systems but now and again these are not enough to create the intended system. An example of this is the modelling of the thermohydraulic energy transfer between a source (central heating plant) and a sink (consumer) in a district heating network. Since the district heating network consists of pipes and pumps between the producer and the consumer, modelling the thermohydraulic energy transfer is a matter of concern. This behaviour is not possible to model with the default components and hence a new component that could ensure modelling the thermal and hydraulic characteristics of the district heating network has to be created. The component thermal behaviour is modelled as a function of the hydraulics of the flow (flow rate, thermal losses).

2.3.1 Component Types and Prerequisites

In physical Modelling, there are two types of models:

- Behavioural – A model that is implemented based on its physical behaviour, described by a system of mathematical equations. An example of a behavioural block implementation is the Variable Orifice Block. [22]
- Composite – A model that is constructed out of other blocks, connected in a certain way. An example of a composite, or structural, block implementation is the 4-Way Directional Valve block (available with

SimHydraulics block libraries), which is constructed based on four Variable Orifice blocks. [22]

Simscape language enables to create new behavioural and composite models when design requirements are not satisfied by the libraries of standard blocks provided with Simscape and its add-on products.

A prerequisite to creating components is having the appropriate domains for the component nodes.

2.3.2 Creating a Component

Prior to creating a new custom component, it is necessary to define a component model class by writing a component file. It typically contains the following sections as discussed briefly earlier in Chapter 2.2.1:

- Declaration
- Setup
- Structure
- Equation

2.3.3 Defining Domain-Wide Parameters

Another type of a custom block is an environment block that acts as a source of domain-wide parameters. For example, one can create a hydraulic temperature block that supplied the temperature parameter to the rest of the model.

2.3.4 Adding a Custom Block Library

Adding a custom block library involves creating new components that model the desired physical behaviour and structure. It may involve creating a new physical domain if the Simscape Foundation domain definitions do not satisfy one's modelling requirements.

After creating the textual component files, these could be then converted to a library of blocks.

2.4 Solvers

The solver's job as stated in [23], to apply a numerical method to solve a set of ordinary differential equations that represent the model. Further the solver

should deliver the accuracy of the simulation that is required and also do this in the shortest possible amount of time. To achieve this Simulink provides different solvers that can be applied to the model. It is possible to choose between fixed-step and variable step solvers and for both of these either an explicit or implicit type can be chosen.

A system becomes linearly implicit when physical modelling blocks are used in the model. Although explicit and implicit are able to solve all systems, implicit solvers are designed specifically for solving stiff problems. Explicit solvers solve nonstiff problems. An ordinary differential equation problem is said to be stiff if the desired solution varies slowly, but there are closer solutions that vary rapidly. The numerical method must then take small time steps to solve the system. Stiffness is an efficiency issue. The more stiff a system, the longer it takes to for the explicit solver to perform a computation. A stiff system has both slowly and quickly varying continuous dynamics. When compared to explicit solvers, implicit solvers provide greater stability for oscillatory behaviour. However, implicit solvers are also computationally more expensive. They generate the Jacobian matrix and solve the set of algebraic equations at every time step using a Newton-like method. Implicit solvers are more efficient than explicit solvers when solving a linearly implicit system. [24]

The fixed-step solver, has as the name implies, a fixed time interval between the calculations that are done. This is called the step size and this remains constant throughout the simulation. The next simulation time is computed as the sum of the current simulation time and the step-size. In the variable step solver the step-size can vary from step to step to keep the simulation within the error tolerances that can be specified.

Whether to choose the fixed step or the variable step solver according to [23] depends on different factors. If the model is to be implemented in a real-time system a fixed step solver should be chosen to simulate the model since the variable step size can give long simulation times, when the simulation time is large, a variable step solver might be desirable during development and testing because it can shorten the simulation time significantly. This time saving is obtained by reducing the number of steps and thus increasing the step size. This can be done when the simulation result is within the error tolerance specified.

From [23] it is found that the implicit or explicit solver type is to be chosen from the knowledge of the model. A model is said to be stiff if the system has extremely different time scales. The explicit solvers are the best choice for systems that are non-stiff, consequently having small differences in time scale, and the implicit solvers are designed for solving stiff problems. The implicit solvers are more stable when having oscillatory behaviour of the system, but also at the same time more computationally expensive. [23]

2.4.1 Choosing a Solver for Simscape

For physical models such as Simscape models MathWorks [25] recommends implicit solvers since these require fewer time steps than explicit solvers. Simscape models are typically considered stiff and therefore the explicit solvers cannot be used or are at least not recommended.

It is also possible to work with a global solver for the entire Simulink model and a local solver in each Simscape part according to [19]. The idea is that different solvers are applied to different Simscape systems so that an implicit solver is used on stiff parts and explicit solver on non-stiff parts [19]. The benefit from this approach is that the simulation becomes more efficient.

Another approach found in [19] is to use local fixed step solvers for each Simscape part and continue to use a variable step global solver for the entire Simulink model. This can be done through the solver configuration block that must be added to each Simscape network. Here the choice is between the default Backward Euler and the Trapezoidal Rule. If the local fixed step solver is used then the global solver will treat this network as having discrete states. Other networks might not use this option and some Simulink or non Simscape parts of the model might have continuous states and therefore the global solver has to be continuous too. Only if all the parts of the model have discrete states the global solver can be discrete.

2.5 Conclusions

As discussed throughout in the subchapter „Modelling in Simscape“, all sections in defining a customised component are explained. This would be combined with the CARNOT toolbox (explained in Chapter 2.6) in Simulink to ensure bi-directional flow between CARNOT and customised Simscape components.

2.6 Modelling in CARNOT

2.6.1 The CARNOT Blockset

CARNOT is a library for MATLAB-Simulink. It is not distributed by MathWorks but is an open source toolbox. It contains elements that are required for the simulation and calculation of conventional and renewable energy systems

The CARNOT blockset provides tools for the easy design, analysis and simulation of models of energy system for use both in the conventional field and also in the field of regenerative systems, with components like solar collectors. Because of the mathematical features of MATLAB and the simplicity of the Simulink block diagram interface, it is a powerful tool for all engineers involved in the field of house heating.

The structure of the CARNOT Blockset is similar to Simulink itself. The elements are organized in blocksets that contain the blocks of one subject. There are blocksets that contain the models of the components of energy systems, like pumps and storages etc., and other blocksets to observe and display the simulation results.

The Toolbox has the following features that bring some advantages to actual simulations in the field of energy systems:

- Simulation of hydraulics and heat transfer at the same time.
- Easy modification of the models and integration of own models because of the standards of MATLAB- Simulink.
- Utilization of the Real-Time-Workshop (Hardware-in-the-loop-test, Software-in-the-loop-test, predictive control, online system identification)
- Guaranteed support and development of MATLAB by MathWorks and thus constant updating of the underlying mathematical algorithms, solvers and functions. [10]

The CARNOT toolbox contains two libraries, the CARSYS Library and the CARNOT Library. In this Chapter, the CARNOT library is explained. The CARSYS library is not relevant for this thesis.

2.6.1.1 The CARNOT Library

The CARNOT Library contains the fundamental blocksets for heating systems components. Furthermore the CARNOT library contain further blocks for more sophisticated modelling:

Blocksets for material properties and basics functions which are useful tools for calculating heating cycles are also included.

The CARNOT library was developed for advanced application in more complex models. There are more options for building-up systems and defining parameters.

The CARNOT library consists of the following Blocksets:

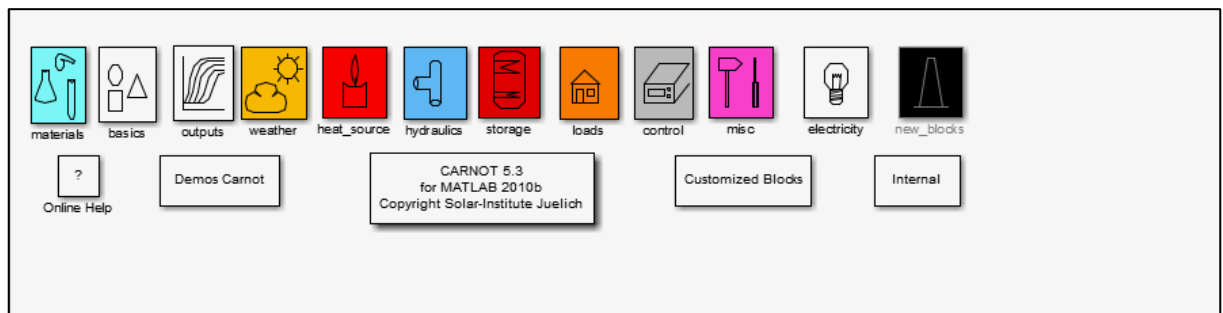


Figure 7: The CARNOT Library

In the following section, an overview of the blocksets is given.

➤ Materials

In this Blockset the material properties of the basic heating fluids are calculated in functions that are collected in the Carlib Library.

The Library actually contains functions for the calculation of the following fluids:

- water
- air
- cotton oil
- silicone oil
- mixture of water and glycol (percentage 0..1)

and it calculates the material properties

- density
- thermal conductivity

- heat capacity
- kinematic viscosity
- enthalpy (only for water and air)
- entropy (only for water and air)
- prandtl
- specific volume
- evaporation enthalpy (only for water)
- vapour pressure (only for water)
- saturation temperature (only for water)

➤ **Basics**

The basics blockset contains some useful function for the calculation of fluid dynamic values and characteristic numbers, e.g. the Reynolds or Prandtl number, and the velocity or pressure drop.

➤ **Outputs**

Visualization blocks for displaying the mass flow rate, the temperature and the pressure from the THV (Thermo-Hydraulic-Vector) which contains all the information about the actual state of the fluid and is passed from block to block, during the simulation. Moreover blocks for displaying the solar radiation, an energy meter to calculate the energy difference between the THV entering and exiting the same block, and a block that calculates and displays the actual collector efficiency are included.

➤ **Weather**

In this blockset the models for weather simulation can be found. Weather data is required for the input values for a large number of blocks, for example as input values to the collector in the form of radiation data. Weather data is processed for different time periods, from monthly average values to hourly values. The pre-processing weather generator includes discrete models for the weather variables radiation, temperature, relative humidity and wind speed. Blocks for the processing and adaptation of weather data are included, e.g. recalculation of radiation data on inclined

surfaces and adding azimuth and zenith angle of the sun for a specified location.

➤ **Heat Sources**

This blockset corresponds to the Simulink Source Blockset. It contains models of various heat sources for energy systems, for example heat exchangers, heat pumps and electric heating. Regenerative components are included, with a solar flat plate collector and a parabolic trough collector.

➤ **Hydraulics**

This blockset uses elementary hydraulic elements which are found in house heating systems to build-up hydraulic cycles. The common hydraulic elements such as valves, Tee-pieces and pipe connections are contained. There are also blocks for the application of the Real-Time-Workshop which introduces some limitations to the modelling of the components (no algebraic loops).

➤ **Pumps**

This blockset contains the hydraulic sources in the form of pumps and a thermosyphon block. The pumps differ due to the mass flow rate they produce. Different models for the pump characteristics are included, for example a pump with constant mass flow rate, a pump with user-definable characteristic, a manufacturer fitted characteristic and as mentioned above one with a thermosyphon. As in the hydraulics Blockset there are separate models for Real-Time-Workshop applications.

➤ **Storage**

This blockset is made up of different kinds of water and ground storages. Various models are included from a simple water storage system to storages with heat exchangers and water supply at user definable positions, as well as two ground storage models.

➤ **Control**

The blockset contains both controllers (actually a bang bang controller) and measurement device blocks for temperature, massflow and climatic conditions. In the measurement devices the temperatures are transmitted with a time delay to model the real behaviour of measurement cycles.

➤ **Misc**

In this blockset various elements are evaluated. For example there is a phase check block, which tests whether the fluid is still in the right phase, e.g. if water is still liquid. Furthermore there are setting blocks, which can set the temperature within the Thermo-Hydraulic Vector to a certain value in order to model definite boundary conditions.

2.6.2 CARNOT Vector Definitions

2.6.2.1 Thermo-Hydraulic Vector (THV)

The Thermo-Hydraulic Vector (THV) is the common data structure of the CARNOT toolbox. The THV contains all the necessary information about the flow and the energy transfer associated with it. In the blocks where the Thermo-Hydraulic Vector is split up, the calculations are carried out in the block and afterwards, the THV is reassembled with the processed values. Each THV corresponds to a physical pipe connection between components. The information is only transported by the vector, whereas the calculation is performed inside the blocks. Components are connected using the THV. Each block must have at least one entry for a THV, otherwise the block would not have any effect on the state of the flow.

The THV has 20 components from which 10 are actually used and the rest are reserved for the later modification or extension of calculations that may require more data to be passed from block to block.

In cycles without flow diversion, this number of components is fixed. However, in cycles with flow diversion in various branches, the THV is enlarged, since the values of the main cycle are passed through the subcycle. At each flow diversion node, four components are added to the THV. They are the total mass flow and the constant, linear and quadratic pressure drop coefficient. In the

corresponding mixer components, the hydraulic values of the respective subcycle are separated from the THV, evaluated and if necessary fed back to the diverter element.

The structure of the Thermo-Hydraulic Vector is shown in the following table.

Table 2: Structure of the Thermo-Hydraulic Vector in CARNOT

No.	Description	Abbreviation	Physical Unit	Remarks
1	Flow identifier	ID	None	Is set by the simulation, not by the user
2	Temperature	T	[°C]	
3	Mass flow	Mdot	[kg/s]	
4	Pressure	P	[Pa]	
5	Fluid type	Fluid_ID	None	Is set in the pump
6	Mixture of fluid	Fluid_mix	[0..1]	Is set in the pump
7	Diameter last piece	D_last	[m]	
8	Constant coefficient of pressure drop	C	None	
9	Linear coefficient of pressure drop	L	[s/kg]	
10	Quadratic coefficient of pressure drop	Q	[s ² /kg ²]	
11 to 20	Not used			

Physical units in CARNOT are conformed to SI standards. For example the temperature is given in degree Centigrade and not in Kelvin.

2.6.2.2 Weather Data Vector

For simulating the modelled district heating network with decentralized heat generators such as solar collectors, a weather data vector is necessary.

The weather data vector contains the weather conditions for the calculation period. It is calculated from measurements over a long period of time. Averaged data of monthly measurements are pre-processed discretely to generate hourly values of relevant weather data. Correlations for the temperature, the radiation, the relative humidity and the wind speed are used to generate the hourly values. [10]

The format of the weather data in the CARNOT toolbox is given as follows:

Table 3: Format of the weather data in CARNOT toolbox

Column	Description	Units
1	Time	[s]
2	Timevalue YYYYMMDDHH (Y is the year, M is the month, D is the day, H is the hour)	[°]
3	Zenith angle of sun (at time, not averaged)	[°]
4	Azimuth angle of sun (0° = south, east negative)	[°]
5	Incidence angle on surface (0° = vertical)	[°]
6	Direct solar radiation on surface	[W/m ²]
7	Diffuse solar radiation on surface	[W/m ²]
8	Ambient temperature	[°C]
9	Radiation temperature of sky	[°C]
10	Relative humidity	[%]
11	precipitation	[m/s]
12	Cloud index (0 = no cloud, 1 = covered sky)	[0.. 1]
13	Station pressure	[Pa]
14	Mean wind speed	[m/s]
15	Wind direction (north = 0 deg; west =	[°]

	270 deg)	
16	Incidence angle in plane of vertical and main surface axis (the main axis is parallel to heat collecting pipes in a collector: It is pointing to the center of the earth)	[°]
17	Incidence angle in plane of vertical and second surface axis (the second axis is in the surface and a vertical on the heat collecting pipes in a collector, it is pointing to the horizon)	[°]
UNKNOWN	Set -9999 for unknown values	

2.6.3 Example of a solar hot water system in CARNOT

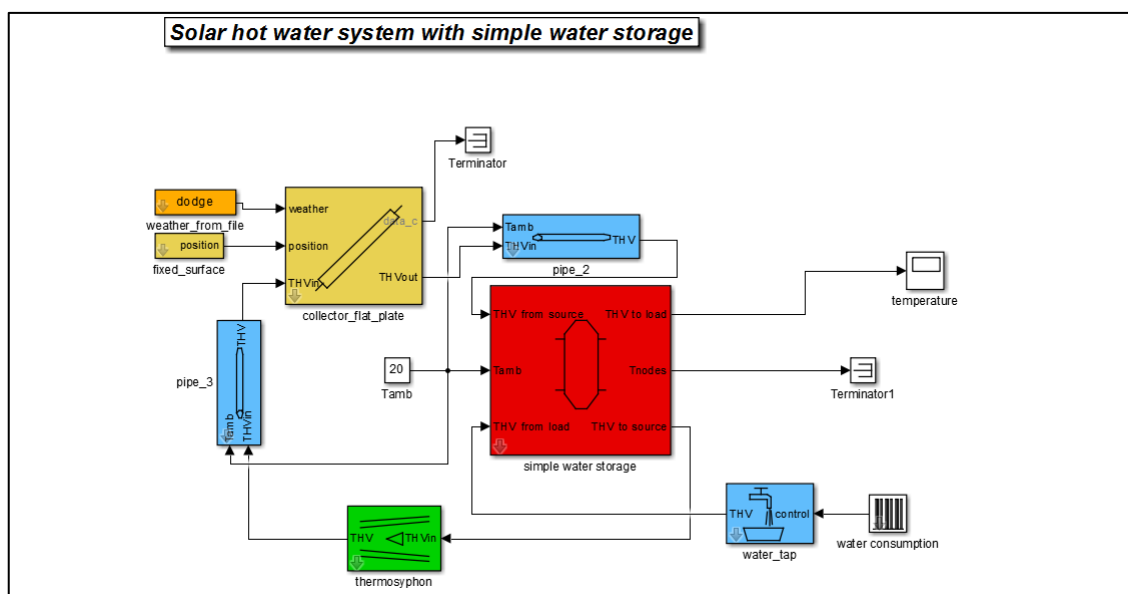


Figure 8: CARNOT model of a simple solar hot water system

Figure 8 shows a CARNOT model of a simple hot water system that consists of a solar collector as heat source, and a simple water storage to store and buffer the solar energy and supply the heat to a consumer. The model consists of different blocks from the different blocksets of the CARNOT library. The components are connected by the Thermo-Hydraulic-Vector (THV), the

common data structure of components of the CARNOT systems which contain all the fluid and the thermodynamic information of the actual fluid state. The THV is fed as an entry into each block, the calculations are performed inside the block and then the THV is reassembled with the calculated values and passed to the subsequent block as an entry.

The system consists of two cycles, the collector or charging cycle and the consumer or discharging cycle.

In the discharging cycle, the cold water from the water tap is supplied to the storage and the hot water is released from the storage. The cold water consumption is modelled by a water pump with constant mass flow rate (the water tap block) and a repeating sequence. The discharging cycle is not a closed cycle, but as described above, the water supply is modelled by a periodic cycle of consumption and the load is linked to a visualization block.

The temperature inside the storage can be displayed at certain node temperatures. These nodes correspond to the nodes for the calculation of the storage. The number of nodes can be specified in the mask. The temperature of all the nodes is terminated in this case.

In the charging cycle cold water from the storage is pumped by means of thermosyphon effects to the collector. The thermosyphon block does not add any pumping power to the fluid but calculates the massflow from the balance between thermal heat and friction.

The following pipe connection block calculates the heat losses by conduction to the environment which is set at 20 °C, by conduction in axial direction and the pressure drop in the pipe connection between the elements. The block symbolizes the whole hydraulic connection between the blocks. For the hydraulic calculations a block is always needed, because no calculations are carried out in the THV. Only information about the fluid states is passed from block to block by the THV.

In the collector, the heating of the fluid is determined on the basis of the incoming weather data and the collector parameters. To model the solar conditions of one year, the toolbox contains a weather data file that was preprocessed from monthly averaged weather data to hourly values. These data files are formatted to match MATLAB-Simulink requirements for inout data

from data files. More information on the format of this weather data vector has been discussed in the Section 2.6.2.2.

2.7 Comparison between CARNOT and Simscape

The customised components in Simscape that have been modelled need to be tested and validated with CARNOT for consistency in results. This section describes a simple parallel flow which is modelled using customised components in Simscape. The results of the simulation of the model in Simscape are compared against the results with the same parallel flow modelled in CARNOT. Based on the credibility of the results in Simscape, the district heating network is modelled using the same customised components. This is later discussed in chapter 3.

2.7.1 Modelling of a Parallel flow diversion in CARNOT

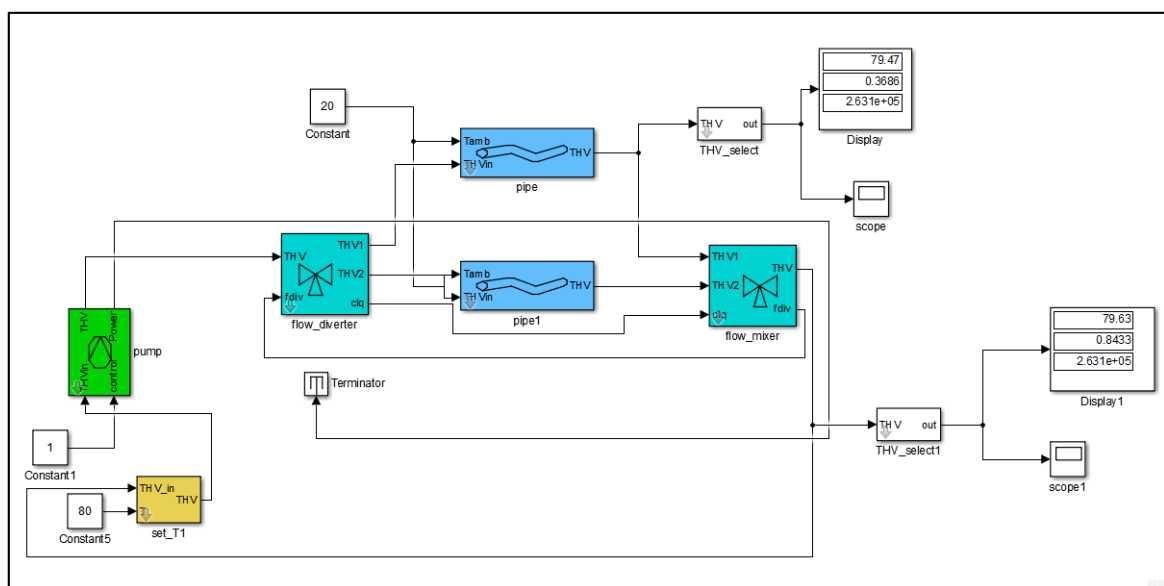


Figure 9: CARNOT model of a parallel hydraulic cycle

The Figure 9 demonstrates a hydraulic cycle with two parallel pipe branches modelled in CARNOT. This is the classical cycle of a bypass: in one branch is a hydraulic load, while in the other branch the fluid is by-passed to the load. All bypass cycles must contain a flow diverter and a flow mixer.

In the CARNOT library two types of flow diverter are included, one for a fixed ratio between the two branches and one for a distribution according to the pressure drop in the respective branch.

The set_T block is the source for setting the temperature of the cycle. It has two ports which is a Temperature port where a constant block of 80 °C is connected thereby providing the set temperature at every point of the simulation. The other port passes the THV information along the cycle.

The pump is the energy source of the cycle which supplies the necessary energy to overcome hydraulic flow resistance of the pipes and to accelerate the fluid.

The fluid enters the bypass cycle in the diverter. In this particular case, the pressure drop in the diverter is not considered, but there are components in the CARNOT library that also calculate the pressure drop of the diverter itself.

The simple pipe connection considers the thermal capacity of the wall, heat losses to the environment, heat conduction between nodes and heat transfer by the mass flow, frictional losses due to the roughness of the wall. Furthermore, this block presumes the pipe is straight with no bends. As a final feature, the linear and the quadratic pressure drop coefficient are parameters which can be entered directly into the mask. In the „pipe with capacity“ block, one can specify the bends and wall roughness to be considered.

The flow mixer sums up the pressure drop of the respective branch and performs the mixing of the two fluid streams by means of an energy balance. Moreover the pressure drop of the bypass subcycle is calculated in the mixing block and merged to the pressure drop of the main cycle.

The mixer feeds back the pressure drop coefficients to the diverting block which is used to calculate the fraction of the complete flow for the two branches and calculates the pressure drop of the entire subcycle.

To visualise the temperature, mass flow and pressure along the two branches, the CARNOT scope block with a select THV block separating the mass flow \dot{m} , temperature and pressure from the THV is included.

2.7.2 Modelling of a Parallel flow diversion in Simscape

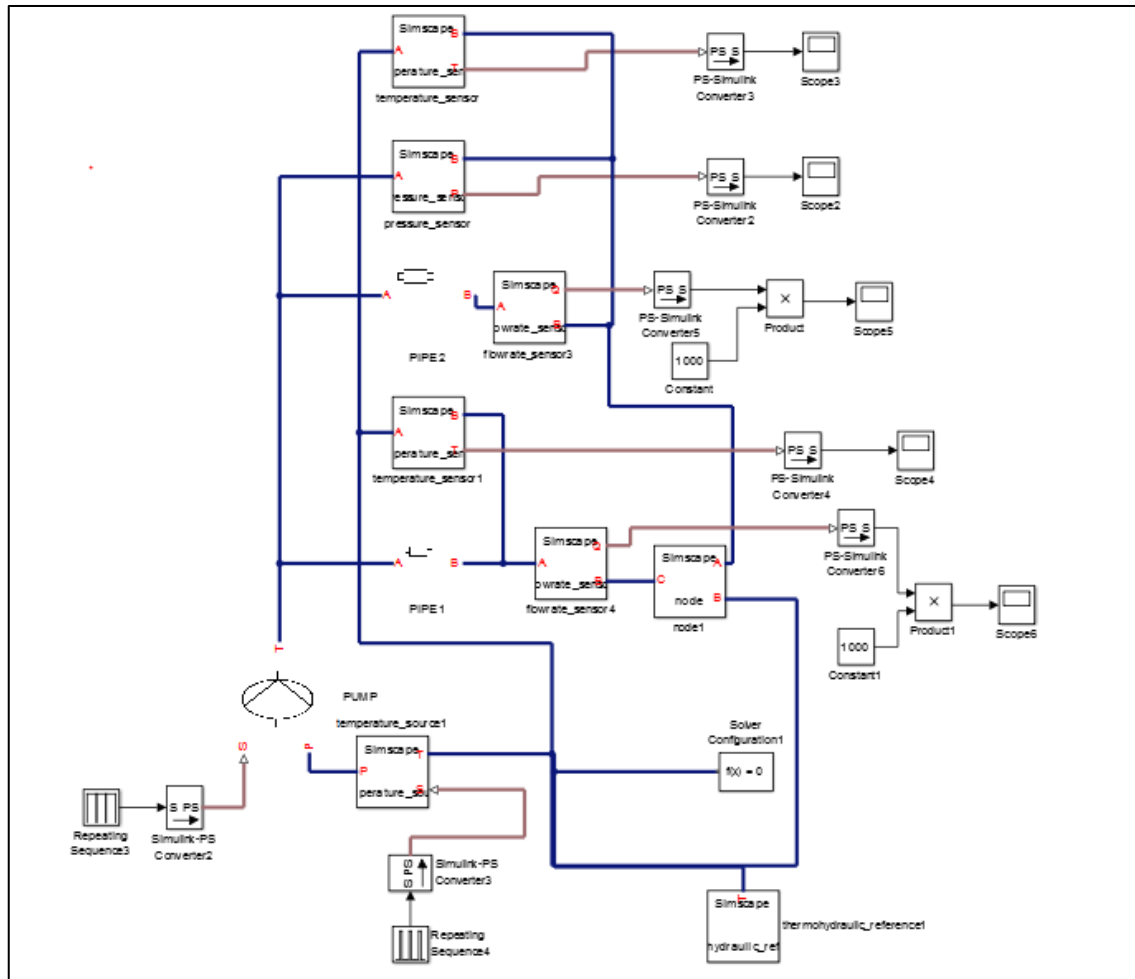


Figure 10: Simscape Model of a parallel hydraulic cycle

Figure 10 demonstrates a hydraulic cycle with two parallel pipe branches modelled in Simscape. This is analogous to the model discussed in the Section 2.7.1. In the figure above, all components such as the Pump, pipe, temperature source, sensors (flow rate, temperature, pressure), thermohydraulic reference and node are customised components. These components are modelled under the thermohydraulic domain. The codes for these individual components and the thermohydraulic domain are mentioned in the Appendix.

As compared to the CARNOT model discussed in Section 2.7.1, there is no existing flow diverter and mixer. This issue of multi-connecting nodes is solved using a customised „node“ component. The pressure losses along the component „node“ are set as zero. Conservation of energy is the main

governing equation that defines the flow of fluid along the pipes through this node. Mathematically, it is given below in *Equation 2.1*.

$$\dot{m}_1 C_p T_1 + \dot{m}_2 C_p T_2 = \dot{m}_3 C_p T_3 \quad (\text{Eqn.2.1})$$

Conservation of mass flow rate is another equation that defines the boundary condition in order to define the flow at the node. Mathematically, it can be expressed as in *Equation 2.2*.

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad (\text{Eqn.2.2})$$

Equation 2.2 basically states that the mass flows (\dot{m}_1 , \dot{m}_2) that enter at a certain node leaves the same node as \dot{m}_3 which is the sum ($\dot{m}_1 + \dot{m}_2$) of the two entering flows. Using this principle, the node is modelled in Simscape which is analogous to the mixer in CARNOT.

The pump is the energy source of the cycle and supplies the necessary energy to overcome hydraulic flow resistance of the pipes and to accelerate the fluid. The pump characteristic curve is modelled using the information from the data sheet of a GRUNDFOS Magna3 50-40 pump type. [27]

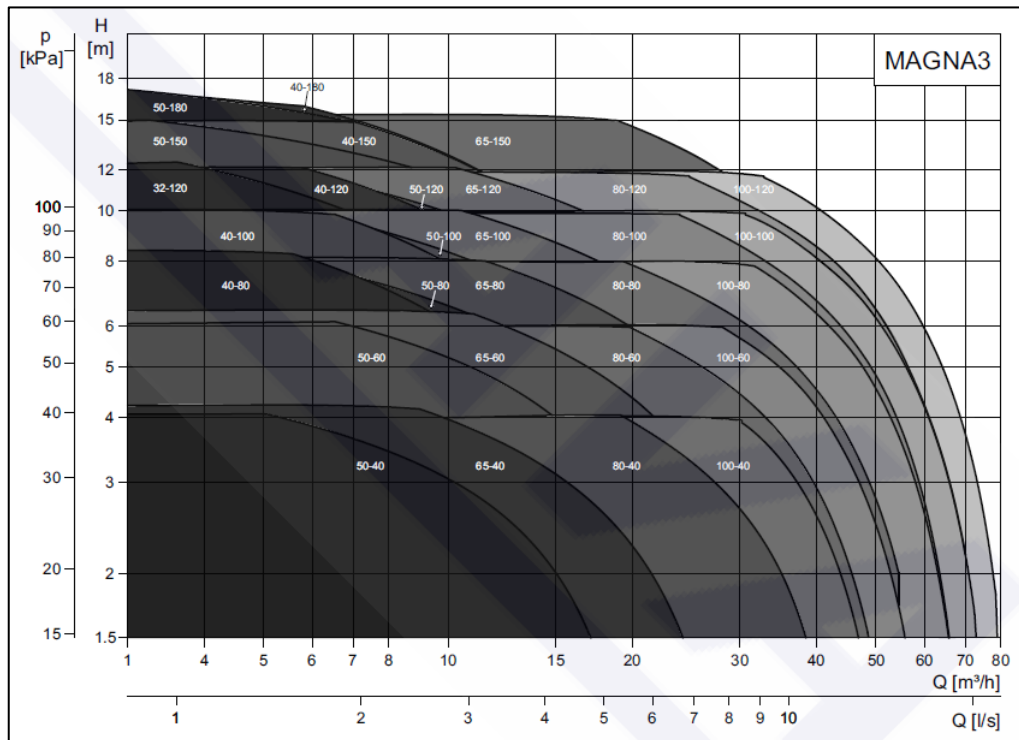


Figure 11: Characteristic Pump Curve for modelling the pump in Simscape

As per this curve, the pump equations are set based on the conditions when the flow rate is either greater than or equal to 0.0009 m³/s.

Mathematically, when the flow rate (q_f) is greater than 0.0009 m³/s, the pressure drop equation is given as:

$$p = a * q_f^2 + b * q_f + c \quad (\text{Eqn.2.3})$$

Where a, b and c are constant co-efficients that depend on the pump characteristics.

A quadratic interpolation is performed to estimate these parameters (a, b, c).

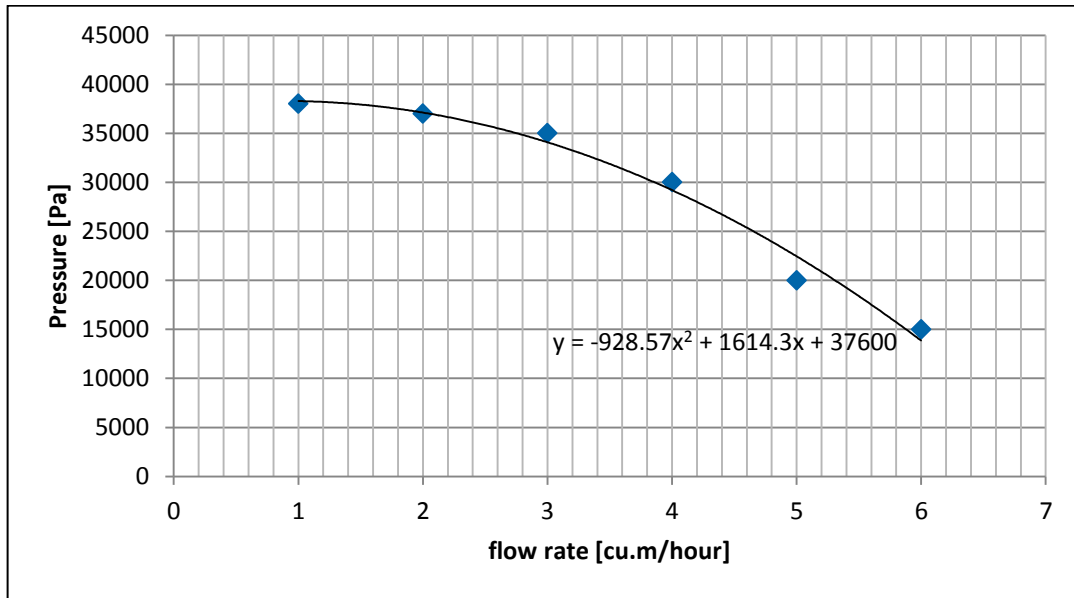


Figure 12: Estimation of parameters a, b and c in the pump characteristic equation

As seen from Figure 12, based on the approximate parameters found through interpolation, the same were used in the pressure equation for the pump. The black curve is the estimated curve which determines the parameters for the equation.

The temperature source is set at a constant temperature at 80 °C. This implies that the temperature of the fluid at the entrance to both the pipes in the parallel hydraulic flow circuit is set to 80 °C.

For the pipe block modelled in Simscape, the equations considered are the pressure loss and the temperature loss equations. The list of equations considering the hydraulic parameters in order to determine the pressure loss across the pipe are mathematically explained below:

$$V_m = q_f / \text{Area} \quad (\text{Eqn.2.4})$$

$$Re = (V_m \times \text{inner diameter}) / \mu \quad (\text{Eqn.2.5})$$

$$f = 0.25 \times \left[\log_{10} \left(\frac{\text{roughness factor}}{3.7 / \text{inner diameter}} + \frac{5.74}{Re^{0.9}} \right) \right]^2 - 2 \quad (\text{Eqn.2.6})$$

$$p = \frac{f \times \text{length} \times \rho \times V_m^2}{2 \times \text{inner diameter}} \quad (\text{Eqn.2.7})$$

where ,

Table 4: Definition of physical terms

Abbreviation	Definition	SI Unit
V_m	mean velocity of the fluid flowing	[m/s]
q_f	flow rate of the fluid	[m ³ /s]
Area	cross-sectional area of the pipe	[m ²]
Re	Reynold's Number	
μ	Kinematic viscosity of the fluid	[m ² /s]
f	friction factor of the fluid flowing through the pipe	
p	pressure loss across the pipe	[Pa]
ρ	density of the fluid	[kg/m ³]

Equation 2.7 gives the pressure losses for the pipe based on the mass flow rate of the fluid through the pipe.

The temperature losses across the pipe are modelled based on the equations given below. The average temperature of the fluid flowing through the pipe is calculated at every instance of time between the two nodes. This is mathematically expressed as below:

$$T_{average} = 0.5 \times (T_A + T_B) \quad (\text{Eqn.2.8})$$

Where, T_A is the temperature at node A (entry of the fluid) and T_B is the temperature at node B (exit of the fluid) of the pipe.

The temperature loss equation across the pipe is mathematically expressed as:

$$t = -\left(2\lambda\pi(T_{average} - T_{ambient}) \times \text{length} \times \left[\log\left(\frac{od}{id}\right) q_f C_p \rho\right]^{-1}\right) \quad (\text{Eqn.2.9})$$

where,

Table 5: Definition of physical terms

Abbreviation	Definition	SI Unit
T_A	temperature at node A of the pipe	[K]
T_B	temperature at node B of the pipe	[K]
λ	thermal conductivity of the pipe	[W/mK]
od	outer diameter of the pipe	[m]
id	inner diameter of the pipe	[m]
q_f	flow rate of the fluid	[m ³ /s]
C_p	heat capacity of the fluid	[J/kg.K]
ρ	density of the fluid	[kg/m ³]

To visualise the temperature, mass flow and pressure along the two branches, the customised temperature sensors, mass flow rate sensors and the pressure sensors are used which are connected to the Scope block.

The Simulink-PS converter are used to convert the Simulink signal to a Physical signal for the input to the pump and the temperature source. Since the outputs of the Simscape components are physical signals, a PS-Simulink converter is used to connect the output of the Simscape blocks to the Scope blocks.

2.7.3 Validation of Customised Simscape Components

The validation of the customised Simscape components are done by analysing and comparing the results with the CARNOT model for the parallel flow as discussed in Section 2.7.1 and 2.7.2 earlier. The simulation run time for both CARNOT and Simscape models for the parallel hydraulic flow is set to 10000 seconds. The basis for the comparison between the two models is the temperature losses across the pipe for different lengths. This is discussed more in detail in Section 2.7.3.1.

2.7.3.1 Temperature losses across the pipe

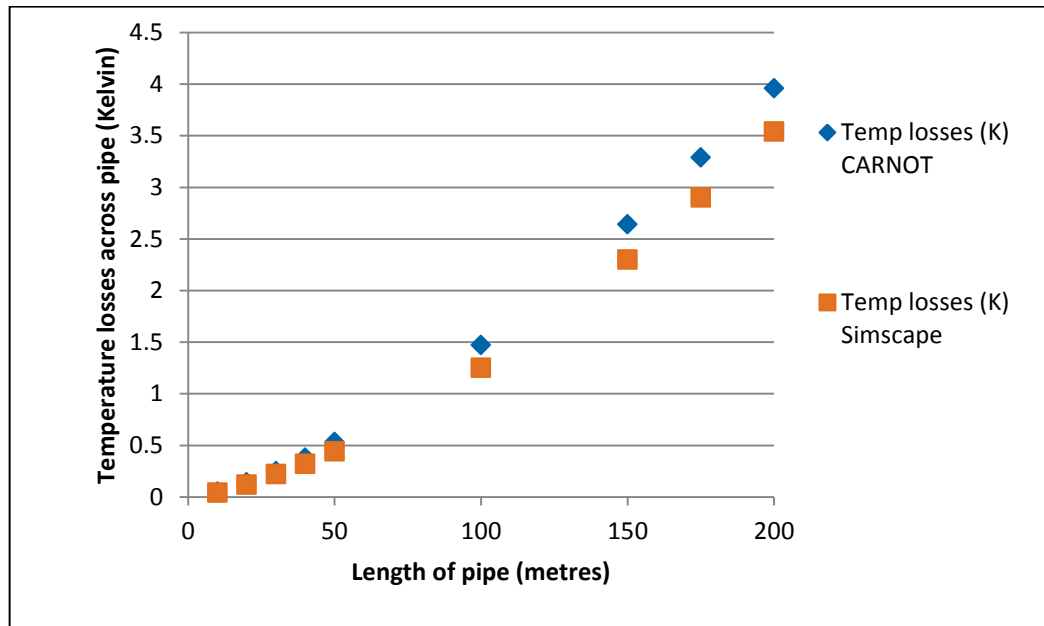


Figure 13: Comparison of temperature losses of the pipe for an inlet temperature of 80 °C in CARNOT and Simscape

The components in the CARNOT open source toolbox have already been validated. There are existing demos that confirm the validity of the CARNOT components. Therefore, the temperature losses across the pipe in Simscape are validated with CARNOT model. Figure 13 shows temperature losses of the pipe for different lengths. The pump is run at a maximum ideal efficiency of 100% in this case. The inlet temperature at the pipes in the two cases in Simscape and CARNOT are set to 80°C. The lengths of the pipe are the variables in the case of validating the Simscape pipe block. The other parameters such as inner diameter, specific heat capacity (C_p), roughness factor, thermal conductivity ambient temperature are set constant in both CARNOT and Simscape models. Figure 13 shows that for various lengths of the pipe, a deviation of the temperature losses as compared to the CARNOT model are observed. For the above simulations, a thermal conductivity of 0.04 W/m.K is considered. The insulation of the pipe in this case is 0.022 m.

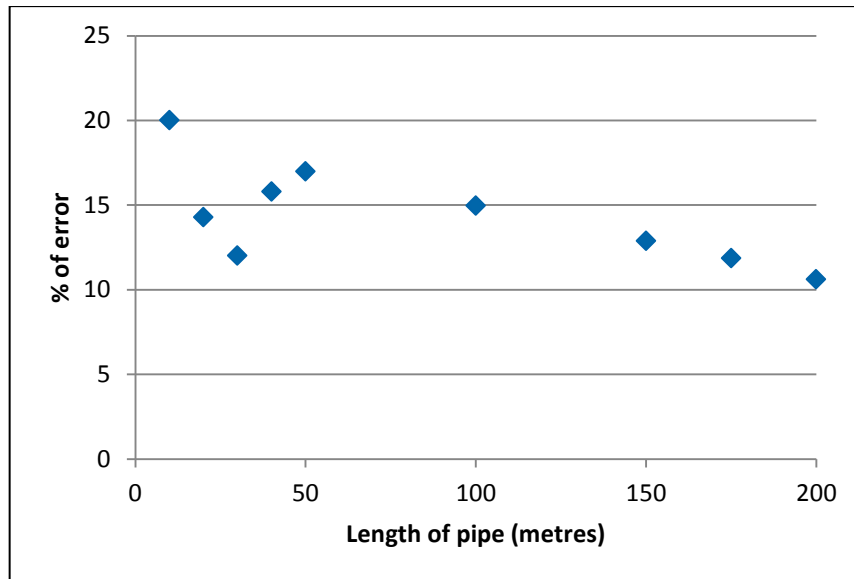


Figure 14: Percentage error of temperature losses as a function of length of the pipe

The percentage error of the temperature losses in Simscape as compared to CARNOT are calculated according to the mathematical formula:

$$\% \text{ error} = \frac{T_{\text{loss,carnot}} - T_{\text{loss,Simsscape}}}{T_{\text{loss,carnot}}}$$

Where $T_{\text{loss,carnot}}$: Temperature losses across the pipe in CARNOT and

$T_{\text{loss,Simsscape}}$: Temperature losses across the pipe using customised Simscape components defined.

Figure 14 depicts the percentage in error of modelling the temperature losses across the customised Simscape pipe block. There is a maximum percentage error of approximately 20 % which occurs at a length of 10m. As the length of the pipe increases the percentage error of the temperature losses across the pipe in Simscape as compared to the validated CARNOT components decreases. This can be clearly seen from Figure 14.

2.7.3.2 Pressure losses across the pipe

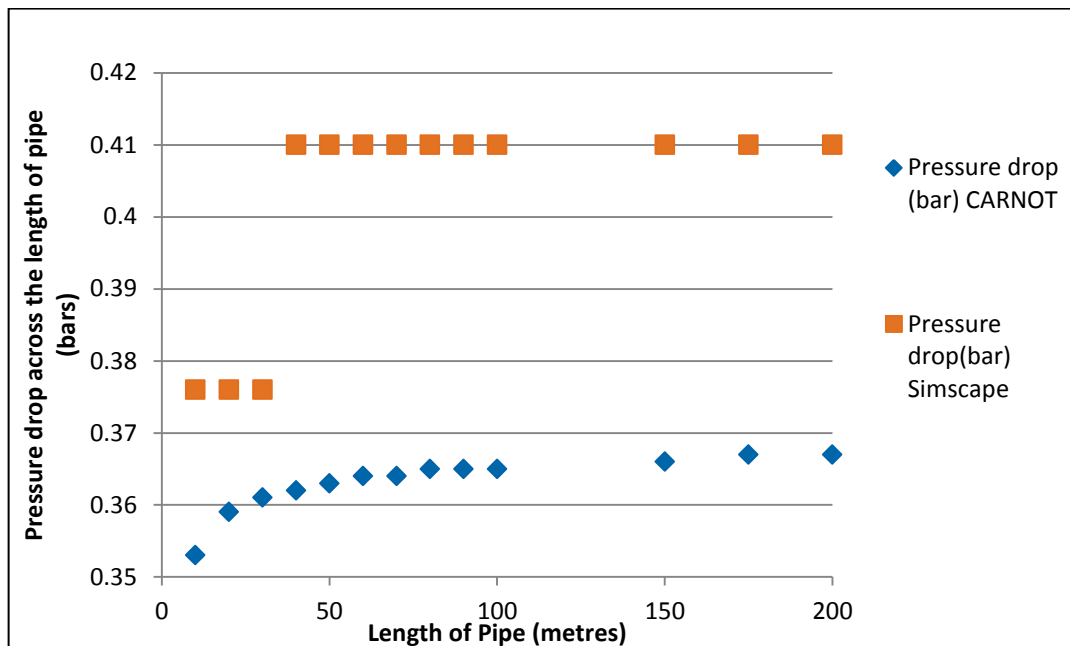


Figure 15: Comparison of pressure drop across various pipe lengths in Simscape and CARNOT

The pressure losses across the length of the pipe are validated with the CARNOT model. The pump is run at a maximum ideal efficiency of 100 % in this case. Figure 15 shows the pressure drops in bars across the pipe for different lengths of the pipe. As along with temperature, pressure is another important parameter to validate in the district heating network, the Simscape components such as pipe need to be validated for the degree of reliability in the district heating model.

In the Simscape model shown in Figure 10, the pump is modelled according to the pump characteristic curve shown in Figure 11. The variable for validation of the pressure losses across the pipe in the parallel flow hydraulic model in Simscape and CARNOT is the length of the pipe. The other parameters such as inner diameter, specific heat capacity (C_p), roughness factor, thermal conductivity, ambient temperature are set constant in both CARNOT and Simscape models. For the above simulations, a thermal conductivity of 0.04 W/m.K is considered. Although the other parameters could be varied and evaluated. Figure 15 shows that for different pipe lengths the pressure losses in Simscape reaches a maximum of 0.41 bars for lengths approximately above 40 metres. For lengths below 40 metres the pressure losses in the Simscape model is approximately around 0.376 bars. This is cross-validated across the

pressure drop in the CARNOT model. There shows a sudden spike in the difference between the pressure losses in Simscape as compared to CARNOT for lengths of pipe above 40 metres. Therefore, to understand the difference in the percentage of error between CARNOT and Simscape, a figure has been plotted (Figure 16).

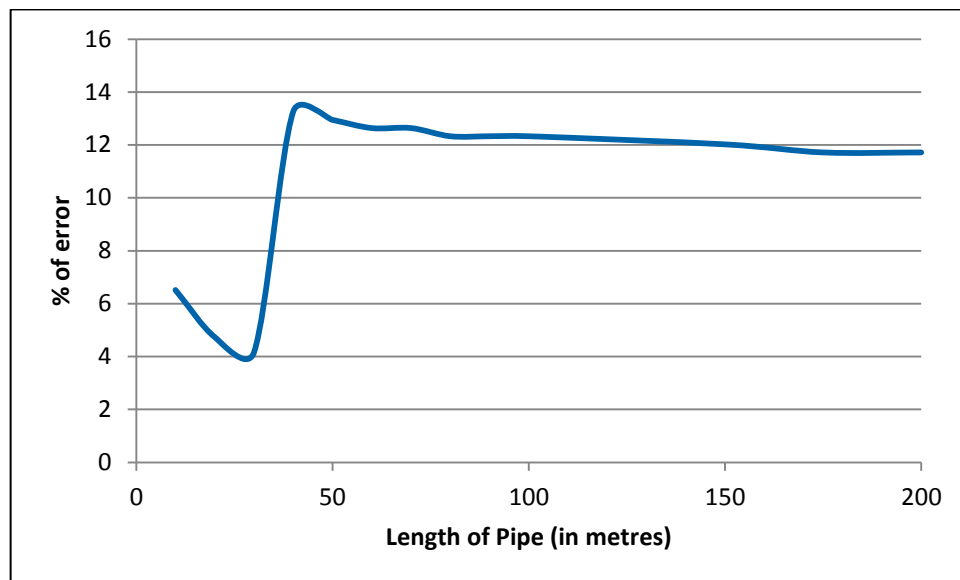


Figure 16: Percentage error of pressure losses as a function of the length of the pipe

Figure 16 shows that the percentage of error in the Simscape model as compared to the CARNOT model. There shows a minimum percentage of error for lengths below 40 metres and a sudden rise in percentage of errors above it. A minimum of approximately 4.15 % error and a maximum of approximately 12.94 % error is observed for varied lengths in the range 10 - 200 m.

2.7.3.3 Validation of mass flow rates across the pipe for different pump efficiencies

The validation of the mass flow for the parallel flow hydraulic model in Simscape is done by considering the mass flow rates through the pipe at different levels of pump efficiency. The pump is run at three cases during a 10000 second simulation; 25%, 50% and 100% efficiencies. Every single scenario of different pump efficiencies are studied against varying pipe lengths. The parameters mentioned such as thermal conductivity, specific heat capacity (C_p), roughness factor, ambient temperature stay the same as mentioned in sections 2.7.3.1 and

2.7.3.2. The plots of the mass flow rates against pipe lengths for different pump efficiencies are shown in the Figures 17, 18 and 19.

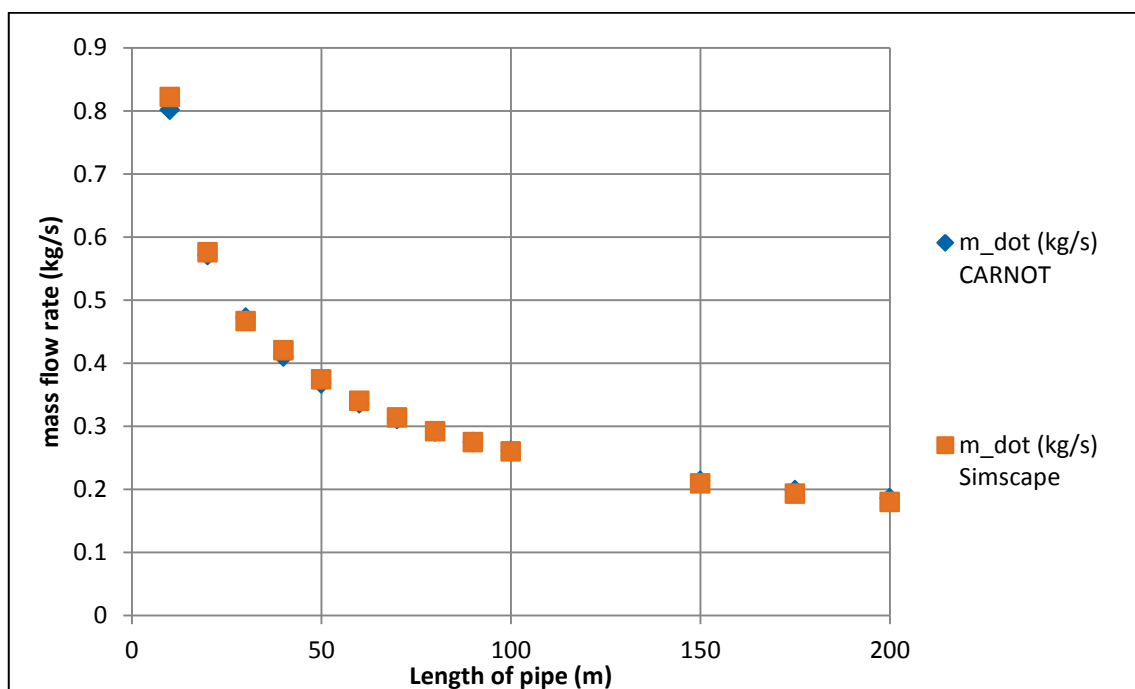


Figure 17: Scenario 1- Variation of mass flow rate versus pipe length for pump efficiency = 100%

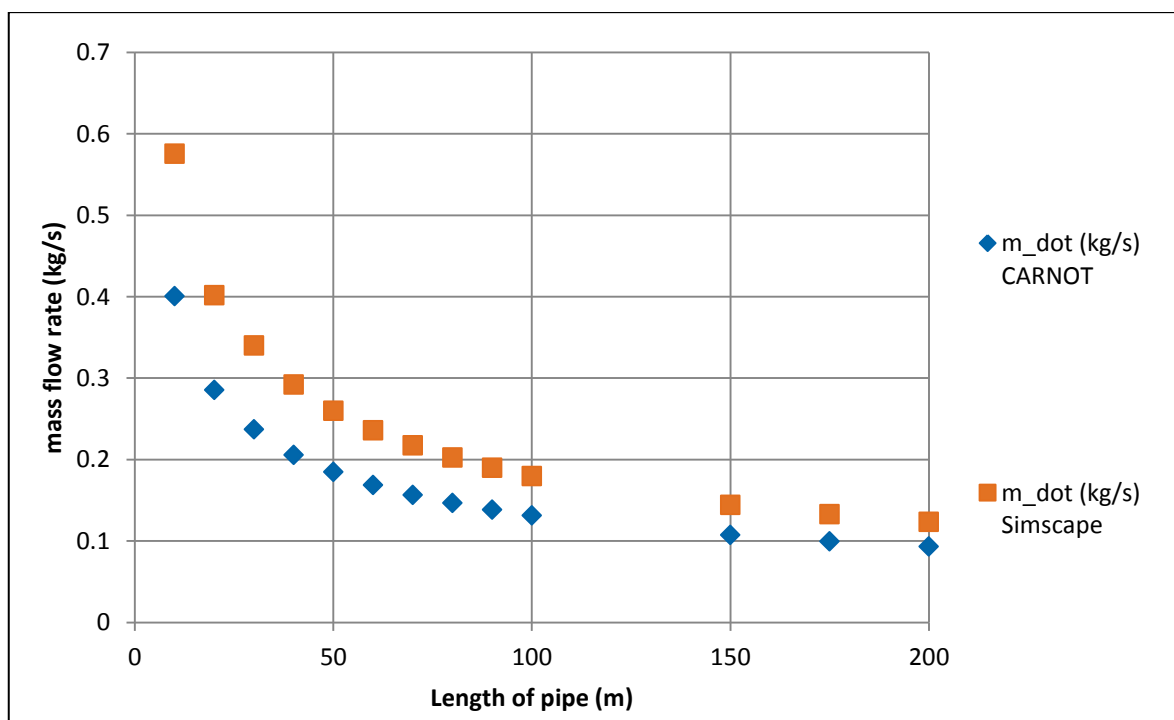


Figure 18: Scenario 2 - Variation of mass flow rate versus pipe length for pump efficiency = 50%

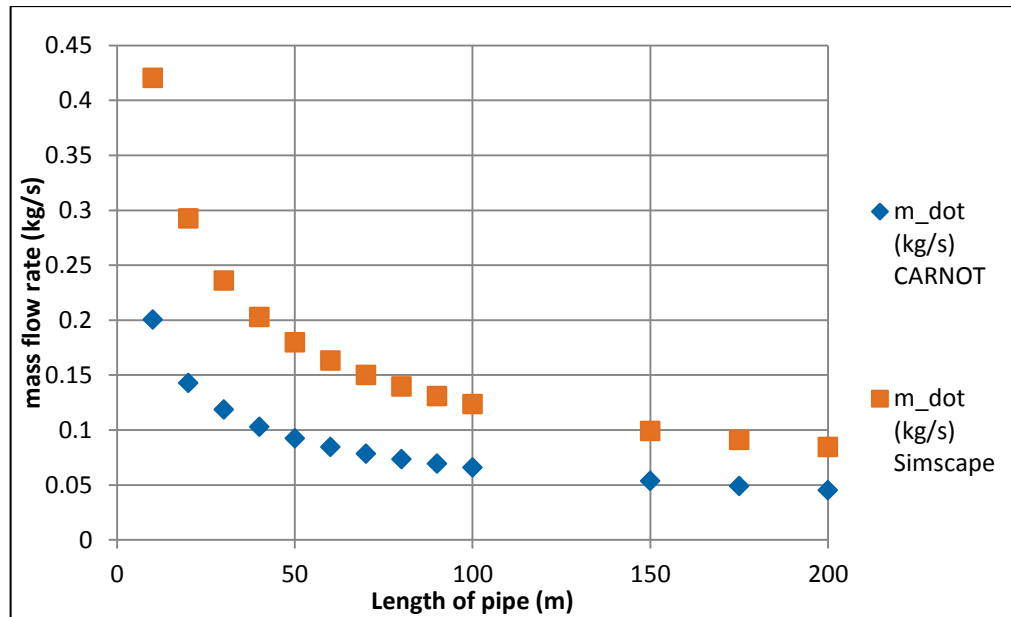


Figure 19: Scenario 3 - Variation of mass flow rate versus pipe length for pump efficiency = 25%

From the above three scenarios in Figure 17, 18 and 19, it can be seen that for decreasing the efficiency of the pump, the degree of accuracy of the pump decreases. This is depicted in Figure 20.

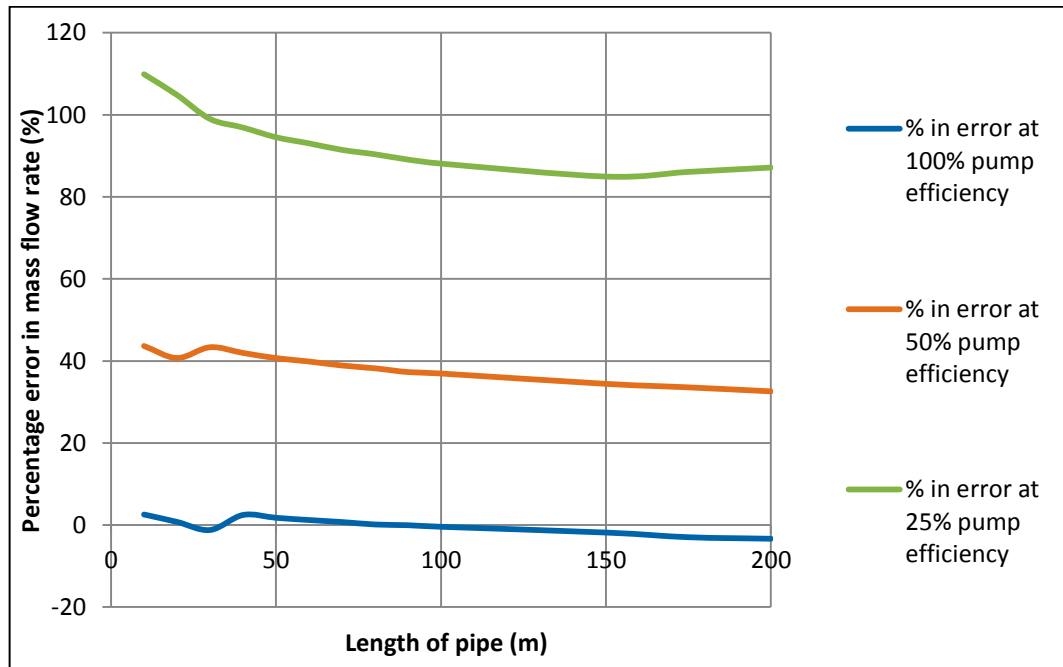


Figure 20: Percentage error in mass flow rate at different pump efficiencies

The Figure 20 shows the variation of the error percentage in mass flow rate in Simscape as compared to CARNOT. It can be clearly seen that for a pump efficiency of 100%, the degree of reliability of the mass flow rates of the

Simscape model as compared to the CARNOT components are almost the same. There appears a maximum percentage error of approximately 2.57% and a minimum percentage error of approximately -3.33% at 100% pump efficiency. As the efficiency of the pump decreases the percentage of error increases. This is seen again in Figure 20. For a pump efficiency of 25%, the maximum percentage in error is approximately 109% as compared to CARNOT model. The minimum percentage error of the Simscape model as compared to the CARNOT model at 25% pump efficiency is approximately 84.94%.

2.7.4 Conclusions

Based on the parallel flow hydraulic model discussed in Section 2.7.1, 2.7.2 using CARNOT and Simscape, certain validation tests are performed as mentioned in sections 2.7.3.1, 2.7.3.2 and 2.7.3.3. From section 2.7.3.1, the temperature losses seem to be in the range of 0.4-0.5 K for lengths of pipe upto 50 metres. For greater lengths of pipe, the losses in the temperature increase. For lengths of the order of 200 m, the percentage error in the temperature losses is approximately 12% . As in a district heating network, the connection between consecutive pipes is approximately in the range of 20 to 30 metres, the percentage of error in the temperature losses above 40 to 50 metres of pipe length could be avoided.

From section 2.7.3.2, the pressure losses across the pipe seem to be negligible for lengths of pipe upto approximately 40 m in Simscape. For lengths of pipe greater than 40m, there is observed a sudden rise in the pressure losses as compared to the CARNOT components. Nevertheless, as in a district heating network, the connection between consecutive pipes is approximately in the range of 20 – 30m; the percentage of error in the pressure losses above 40 meters of pipe length could be avoided.

From section 2.7.3.3, the analysis of mass flow rate of the fluid as a function of different efficiencies of the pump is analysed. It is seen in this section, that the difference in error of the mass flow rates of the fluid flowing through the pipe of different lengths in Simscape increases as the pump efficiency decreases. For lower pump efficiencies the error is higher. At 100% pump efficiency, the error is almost negligible. This is the case that could be used in the district heating network to be modelled which will be discussed in the next chapter.

After validating the customised Simscape blocks with CARNOT blocks, it is then possible to proceed and build the district heating network using these customised blocks. The discussion of building the district heating network with different heat generators is discussed in the next chapter. Although CARNOT would be used to model the consumers and the producers of heat in the district heating network, the district heating network itself (consisting of pipes, flow rate sources/ pumps) would be modelled using the validated customised Simscape blocks.

Chapter 3. Modelling a District Heating Network in CARNOT/ Simscape

The previous chapter explained the tools in CARNOT and Simscape in order to build the district heating network. The customised blocks built in Simscape were validated against the open source toolbox– CARNOT. Chapter 3 explains modelling the district heating network with these customised components validated in Chapter 2 along with CARNOT components used for the consumers and the central heating plant. The input data used for the simulation of the model has also been explained as part of this chapter.

3.1 Modelling of a Central Heating Plant in CARNOT

The central plant superstructure consists of a combination of:

- A heat pump to upgrade heat from a low temperature heat source such as a lake
- A gas turbine cogeneration system to produce both heat and electricity
- An internal combustion gas engine cogeneration system producing both heat and electricity
- An auxiliary boiler directly producing heat. [26]

To simplify this in the modelled district heating network, the combination of all the four points mentioned above are replaced with an electric heating system modelled in CARNOT producing sufficient amount of energy to distribute to consumers in the network. The energy supplied by the electric heating block in CARNOT signifying the central heating plant is able to keep the supply temperature of the district heating network at 80 °C shown in figure 21. The other block components used to model the central heating plant in CARNOT include pump, storage and a controller to set the temperature based on the storage nodal temperature.

The electric heating block which is the main producer of energy modelled in the central heating plant shown in Figure 21 consists of two main inputs which are the THV and the electric heating power. Depending on the number of consumers in the district heating network and the consumption of energy, the

heating power is set at a higher or a lower value to enable the central heating plant to supply the required energy.

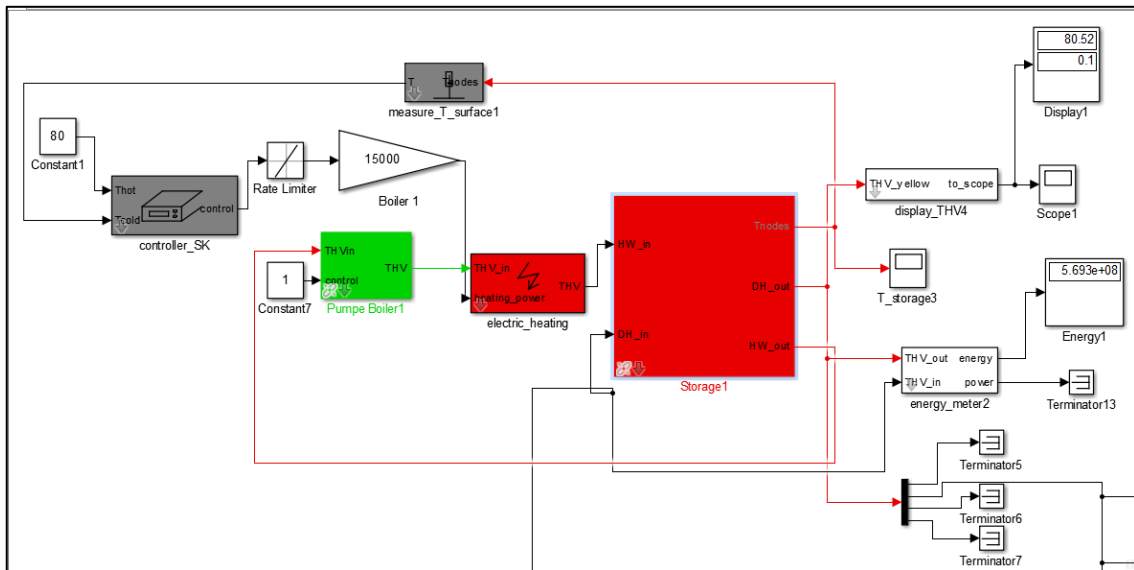


Figure 21: Layout of the central heating plant modelled in CARNOT

In the pump, the mass flow rate is set to 0.4 kg/s. Besides the other parameters that could be adjusted in the pump component block are the ambient temperature, losses to ambient, system pressure. The control input, '1', enables that the pump is 'on'. The input THV to the pump comes from the output of the storage tank. The output of the pump which is a THV is an input to the electric heating block. The storage component block behaves as a buffer storage or a hydraulic shunt heating the return flow of the district heating network with the heat produced by the electric heating block. The return flow of the district heating network is connected to the storage port (DH_in) shown in Figure 21. The output port of the storage (DH_out) is connected to the district heating network which is modelled in Simscape. The flow of the fluid leaving the storage at the port (DH_out) is maintained at 80 °C. This is done by the electric heating block which is controlled by the controller.

The controller tries to maintain a temperature of 80 °C which is set by a constant block at the port T_{hot} . The port T_{cold} is the temperature at a defined height in the storage using the (measure_T_surface) block. The output of the controller is set to zero if T_{hot} or T_{cold} is greater than T_{max} . T_{max} is a parameter which is set to 95 °C in this case.

A closer look at the storage inlet and outlet ports inside the storage mask is shown in Figure 22. The connections to the inlet and outlet of the storage are

modelled using pipe connection to storage blocks. This block transforms the incoming THV vector to a vector which the storage interprets as a flow into the storage fluid. The parameters here include the inlet and outlet height as a relative position from 0 (= bottom) to 1(=top). The fluid at a temperature of 80 °C produced by the electric heating block enters the storage at a position 0.9 (relative to the bottom of the tank; 0) and exits at a position of 0.1 (relative to the bottom of the tank; 0). The return flow from the district heating network enters the storage at a position 0.1 (relative to the bottom of the tank; 0) and exits at a position of 0.9 (relative to the bottom of the tank; 0). During decentralized feed-in, it would be the other way round.

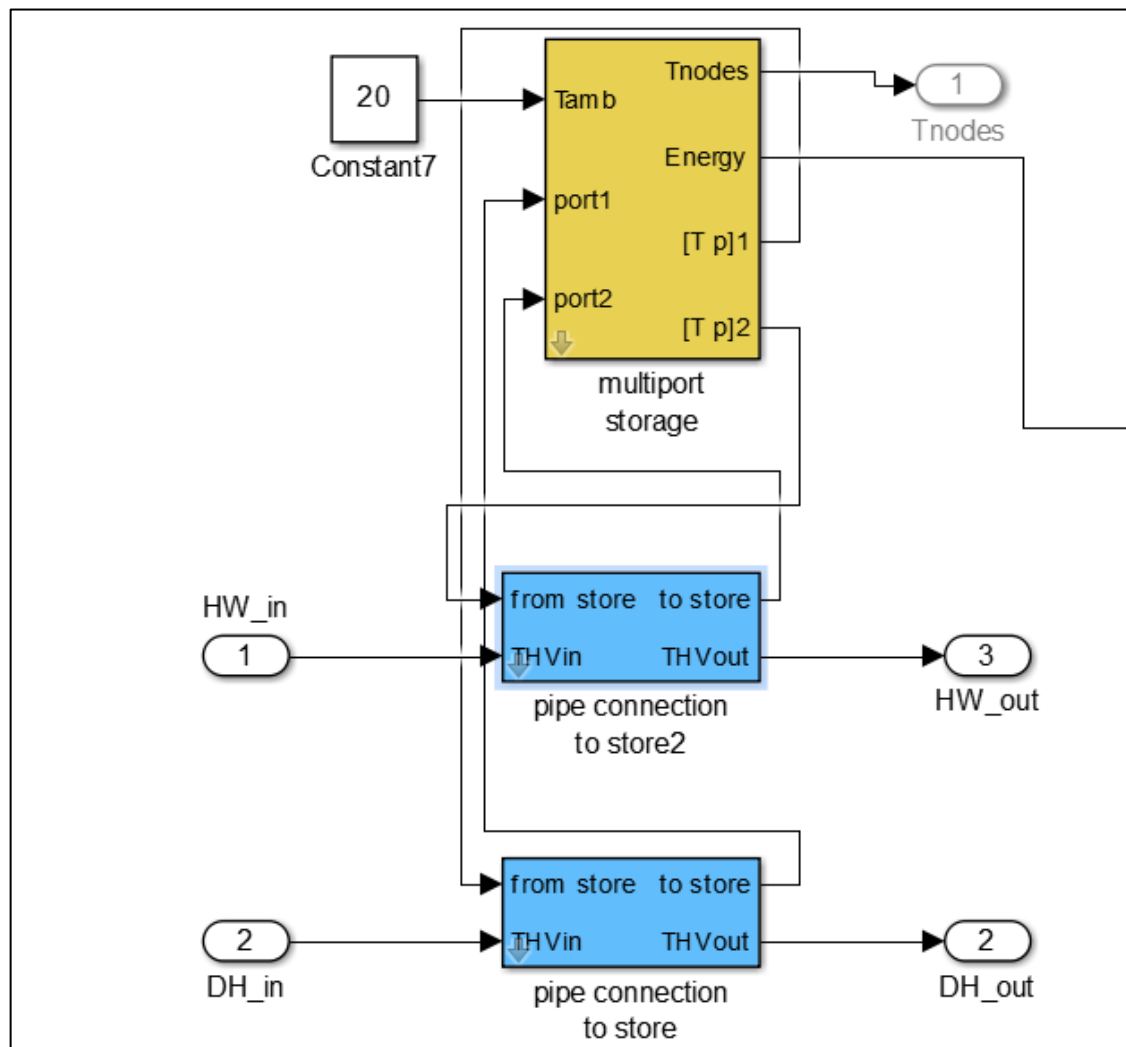


Figure 22: Layout of the connections to the storage inlet and outlet ports

3.2 Modelling of Consumer Buildings in CARNOT

The consumer buildings have been modelled using the block components in CARNOT. The main subsets included in the consumer buildings which are modelled are the thermal storage, decentralized heat generators, space heating and domestic hot water heating. These have been mentioned in details in the following sub-sections within this chapter.

3.2.1 Input data for yearly consumption in a family house / building

The input data for the yearly consumption in a consumer house or building includes the data for the domestic hot water consumption and the space heating consumption.

A simple model in CARNOT is simulated in order to create the yearly consumption for the space heating in a multi-family house or building. The weather data file is based on the weather data vector mentioned in chapter 2.6.2.2. Figure 23 shows the model of a simple multi-family house in order to calculate the space heat consumption of the consumer house.

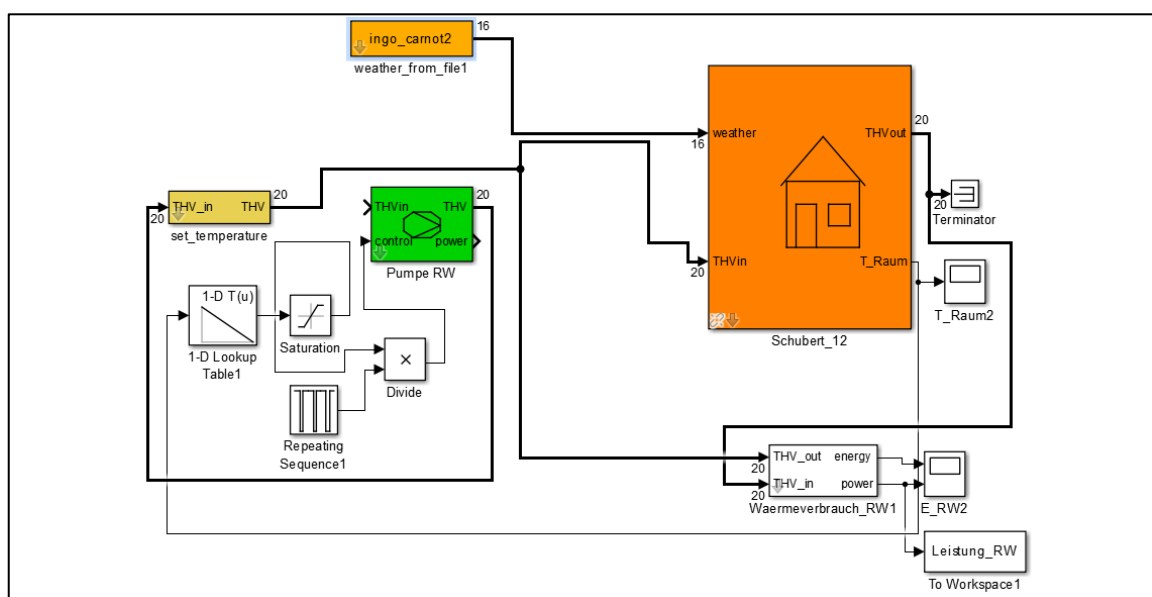


Figure 23: Model of a multi-family consumer building to output the yearly space heating consumption

The model shown in Figure 23 has been modelled using CARNOT component blocks. It is simulated for a period of one year. The output of the above model is the yearly space heating consumption in order to use in the district heating model. The output of the model also gives the room temperature with space

heating during the year which is shown in Figure 24. The power needed for space heating has also been shown in Figure 25.

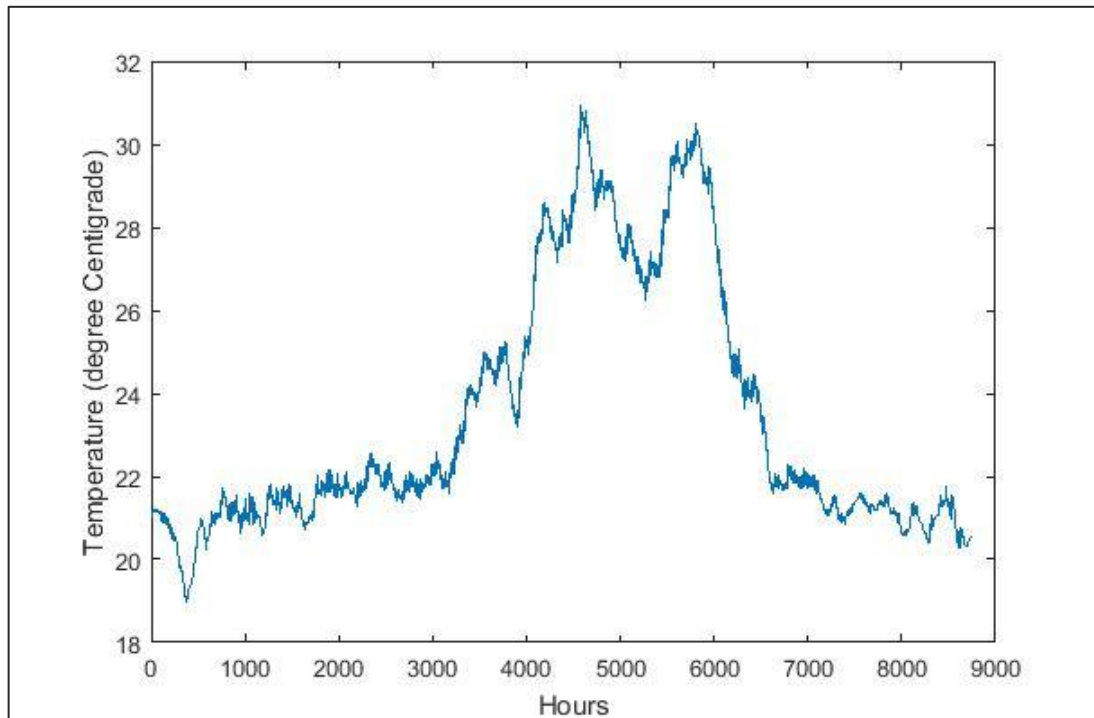


Figure 24: Room temperature over a period of one year for a multi-family consumer with space heating

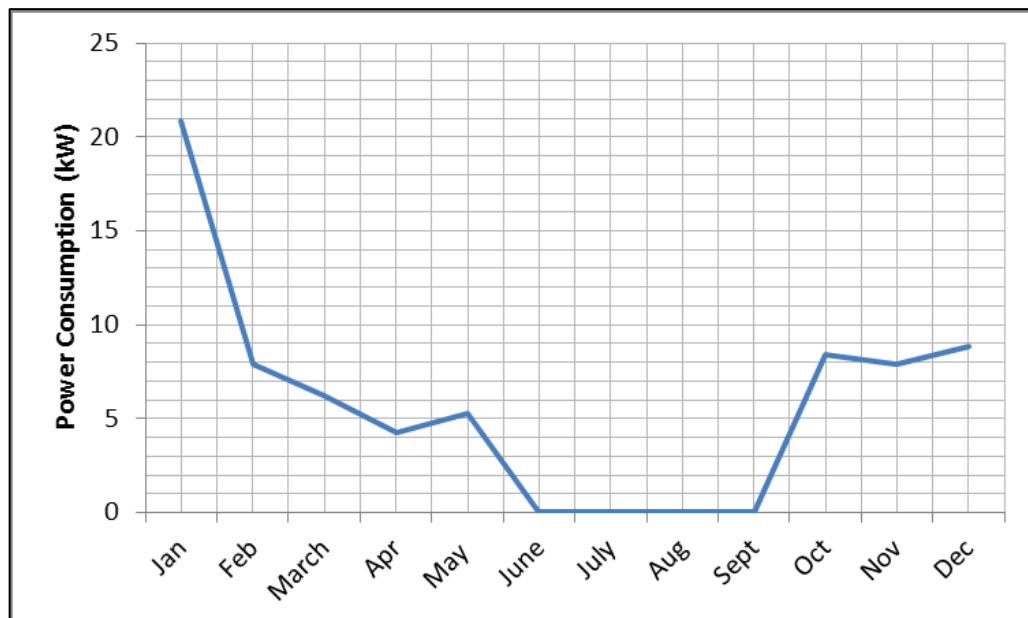


Figure 25: Variation of power consumption for space heating in a consumer building during a duration of one year

The simple house model block from CARNOT is used to model the thermal equations of the house based on the solar gain, internal gain, heating power, losses to ambient, losses to neighbour room. The heating power is transferred by a radiator or floor heating system. The windows have an automatic shading (shading factor) if room temperature rises above 4 K above initial temperature. Here solar gain is defined as follows:

$$\text{Solar gain} = \text{solar radiation on window} \times \text{light transmittance} \times \text{shading factor}$$

The parameters can be varied in the mask block. In this case an initial temperature of 21 °C is considered.

For domestic hot water consumption, a plot describing the variation of power consumption during every month on an average is shown in Figure 26. This is scaled to one year's consumption in the district heating model.

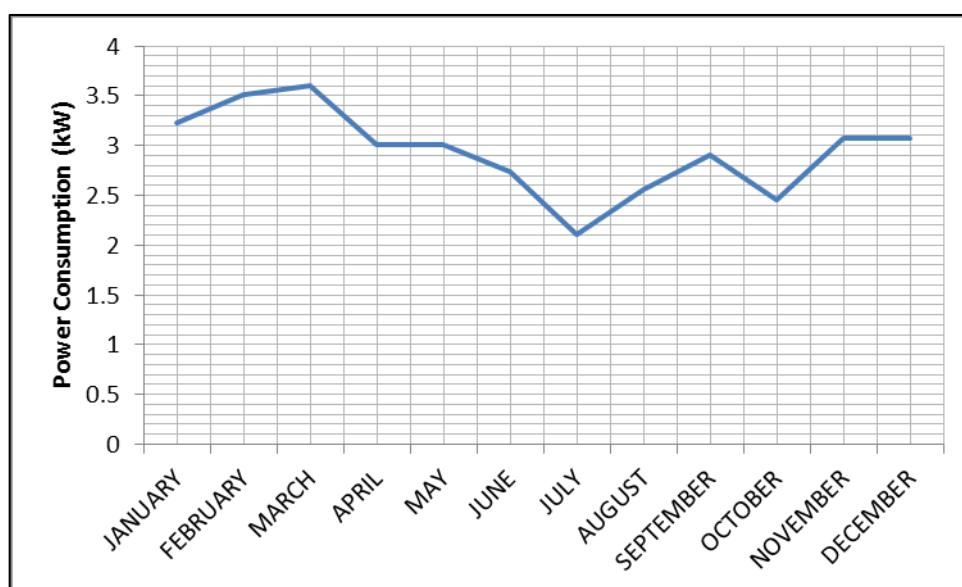


Figure 26: Monthly power consumption of domestic hot water heating purpose in a consumer house used for simulation scenarios

The seasonal effects is added according to VDI 6002 and the variation of the domestic hot water consumption power changes accordingly.

Thereby from the above two Figures (25) and (26), the space heating and the domestic hot water heating consumption power is used as an input data for the simulation of the district heating model.

3.2.2 Modelling of Space Heating System in CARNOT

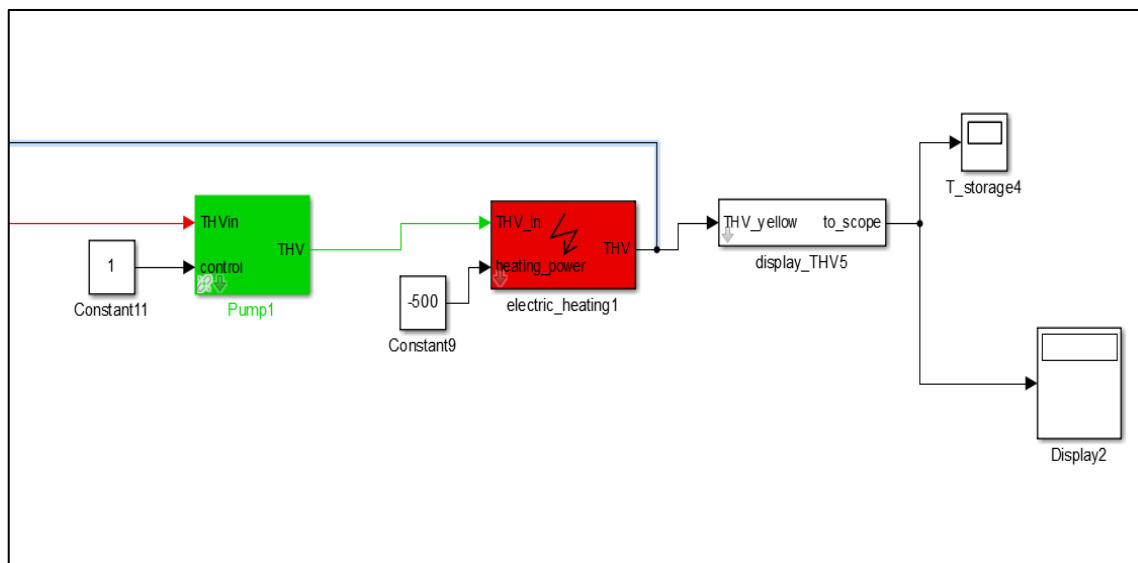


Figure 27: Layout of space heating system modelled in CARNOT

The modelling of the space heating system in the consumer level is done in CARNOT. It includes use of an electrical heating block with a constant negative heating power of 500 in this case. The pump which is at 100% power runs the electric heating system drawing a negative power in order to heat the space in the consumer building. The variable in this case for the space heating system is the heating power of the electric heating block. The above Figure 27 is a simple illustrative model of the space heating system in a consumer's house. The modifications to the above model would be the input of the heating power to the electric heating block. This input for the space heating has been discussed earlier in Chapter 3.2.1 and illustrated in Figure 25. The output of the electric heating block is connected to the storage of the consumer building which is a storage for the domestic hot water and the space heating system. The modelling of the storage is discussed in a later section. The input of the pump is connected to the storage block thereby forming a cyclic loop where the hot water enters the space heating thereby heating the room and returns back to the storage system at a lower temperature than the inlet of the space heating system.

3.2.3 Modelling of Domestic Hot Water System in CARNOT

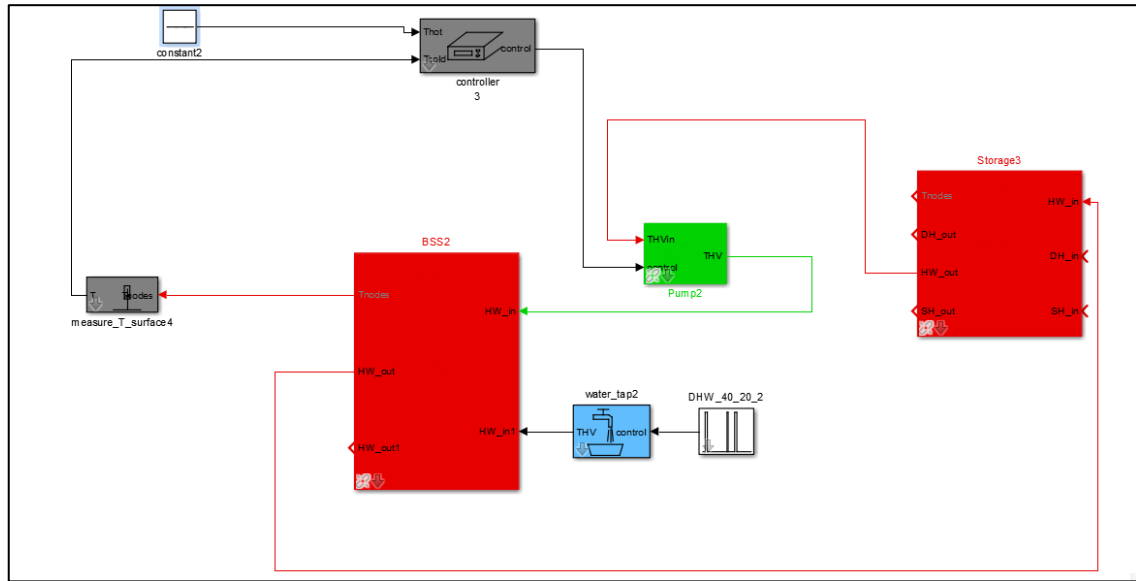


Figure 28: Layout of Domestic Hot Water System modelled in CARNOT

The domestic hot water system at the consumer level is modelled using CARNOT block components as shown in Figure 28. It contains a cylindrical storage block for the domestic hot water. The domestic hot water is controlled by a temperature controller which tries to maintain the temperature of the water at 60 °C throughout. This is shown by the input T_{hot} . T_{cold} is the other input to the controller which is the nodal temperature in the cylindrical storage block. The difference in the temperature between T_{hot} and T_{cold} in the controller controls the functioning of the pump in order to circulate the water from the district heating network into the domestic hot water storage. The *port* HW_{in1} in the above Figure 28 is fed with the input data for domestic hot water consumption in a consumer building. The modification to the above simple domestic hot water system by using the input data of the power consumption discussed in section 3.2.1 and shown in Figure 26 is used in simulating the district heating network. For the above figure, the water tap is modelled with a water temperature of 12 °C and a mass flow rate of 0.14 kg/s.

3.2.4 Modelling of the Substation

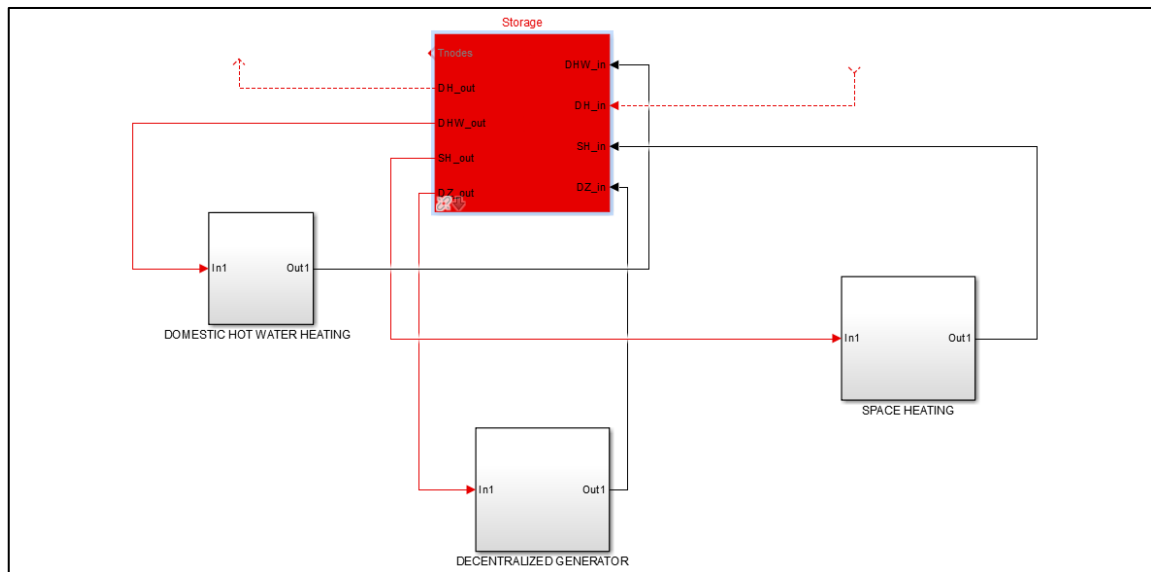


Figure 29: Layout of the consumer substation modelled in CARNOT

The consumer substation which is modelled in CARNOT is a junction to the district heating network and the rest of the consumer station which consists of the domestic hot water heating, space heating system and decentralized heat generators (in some cases). This is shown above in Figure 29. The substation is a modified storage component block in CARNOT. The modification to the default storage component block are the additional pipe connections to the inlet and outlet of the storage. The domestic hot water and the space heating inlet pipes are connected to the bottom of the storage. The water gets heated with the district heating forward flow which is approximately at 80 °C. This then gets distributed according to the type of consumption (either space heating or domestic hot water). The connections to the decentralized heat generator inlet and outlet are at a relative height of 15% and 80% respectively to the storage bottom.

The district heating network inlet and outlet connections to the storage are set at variable heights. This is shown with the dashed line in Figure 29. These are connected to the district heating network modelled in Simscape. The variables are saved in the Simulink workspace. This variable is initially set at a height inlet of 90% relative to the storage bottom and the outlet at 10% relative to the storage bottom. During the simulation, this variable would switch between 0.9 or 0.1 as inlet height to 0.1 or 0.9 correspondingly, depending on whether the

decentralized feed-in is switched on or off. This would thereby make the network with heat generators decentralized in nature.

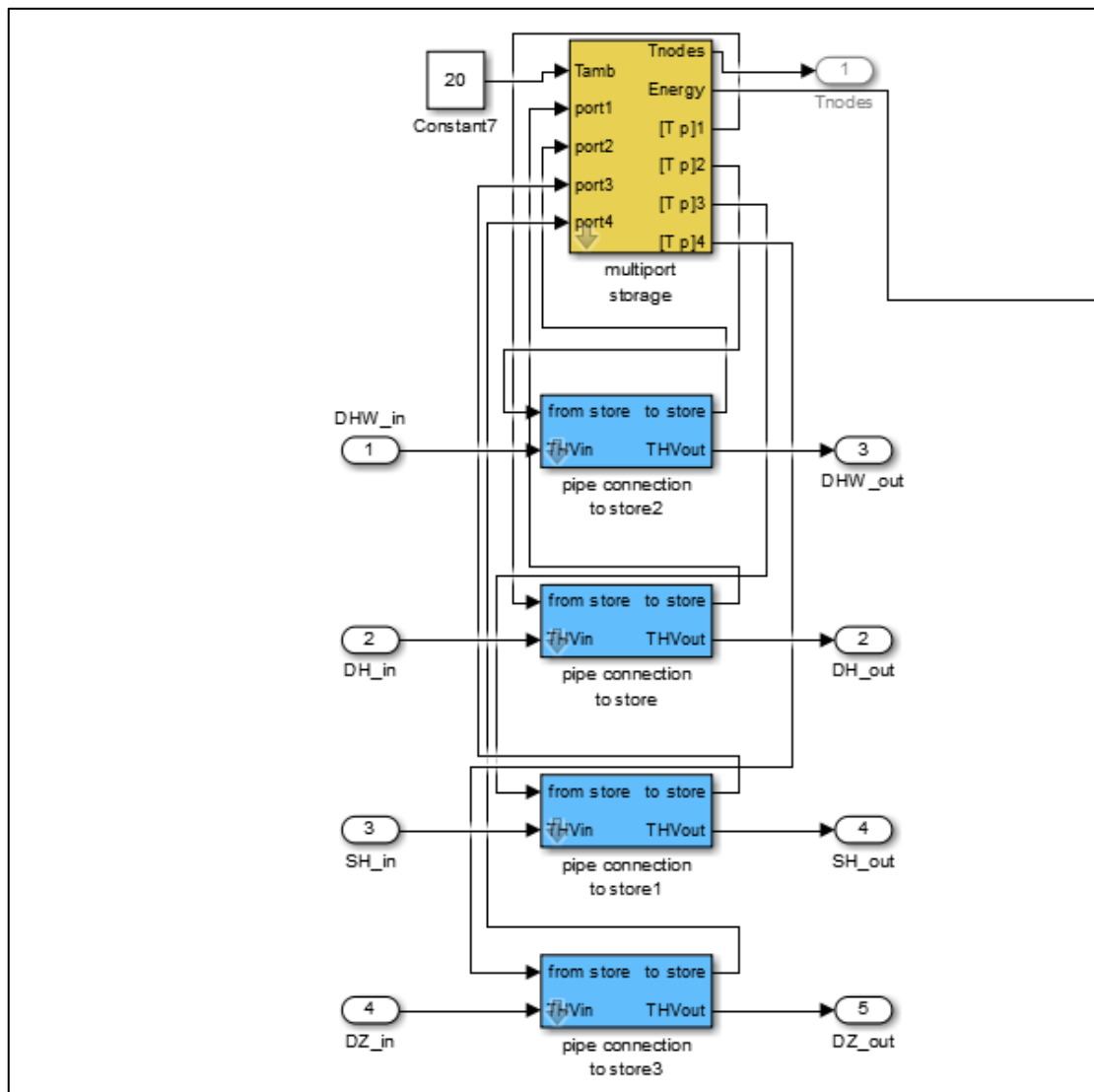


Figure 30: Layout of the consumer substation mask with different pipe connections

As shown in Figure 30, the ports connect the domestic hot water, space heating, decentralized feed-in and the district heating inlet and outlet connections to the storage through the pipes.

3.2.5 Modelling of the Decentralized Heat Generators

The decentralized heat generators are modelled in CARNOT using the predefined components in the CARNOT library. One of the ways in which the decentralized heat generators is modelled is using the solar flat plate collector. The collector model is a one-dimensional multinode model for thermal collectors. The model is based on parameters obtained from measurement, i.e. collector-test results. The collector is divided in „Node“ nodes. The flow is equally distributed among the risers. The energy balance for every node is a differential equation, that is calculated in the S-function. The collector calculates friction losses in the mass flow. [10]

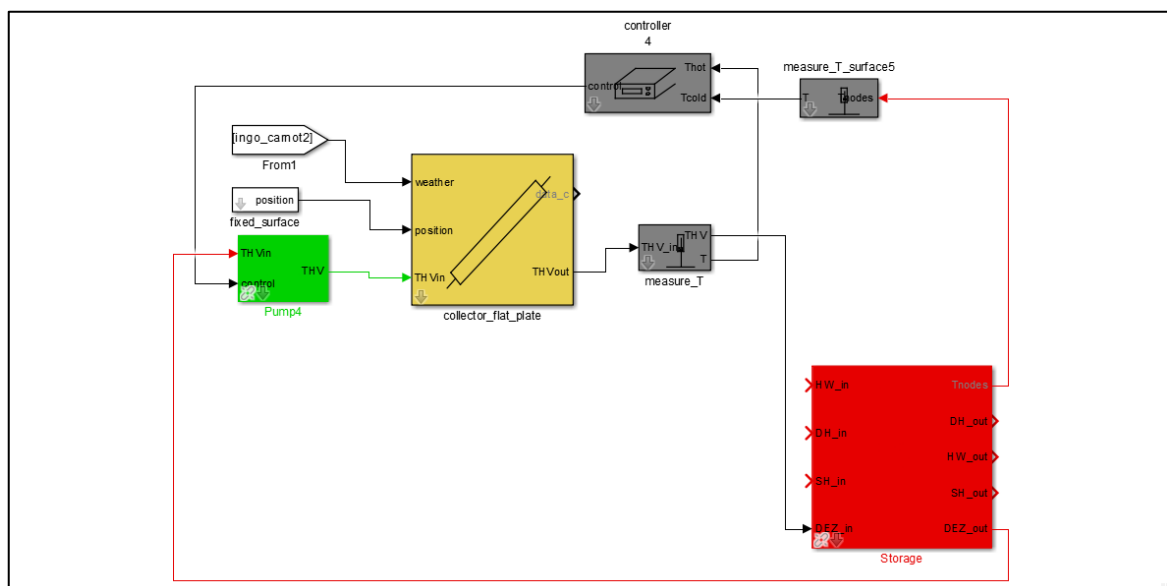


Figure 31: Modelling of the solar flat plate collector decentralized heat generator

As shown in Figure 31, the solar flat plate collector is modelled as a decentralized heat generator in the district heating network. The decentralized generator mainly consists of the predefined collector component, a pump and a controller to define the functioning of the pump to the collector. The water from the storage is pumped through the flat plate collector using the pump which is driven by the controller temperatures. The fluid mass flow enters the storage at the top of the tank and exits through the bottom. This means that the mass flow gets heated through the collector temperature and sent to the storage through the top of the tank. This complete circuit forms a cycle for the decentralized heat

generation in the storage. This heat is then used to heat the water storage for domestic hot water consumption and space heating consumption which is tapped from the storage at appropriate heights.

The inputs to the solar flat plate collector block include the position of the collector and the weather data vector.

The pump connected to the flat plate collector is fed by the controller signal which depends on the temperature difference between the storage and the collector outlet itself. The output of the solar flat plate collector is a THV which is sent to the storage and fed back to the pump THV input. The THV output contains the 20 components of the vector which are passed to the storage.

3.3 Concept of District Heating with Decentralized Heat Generators

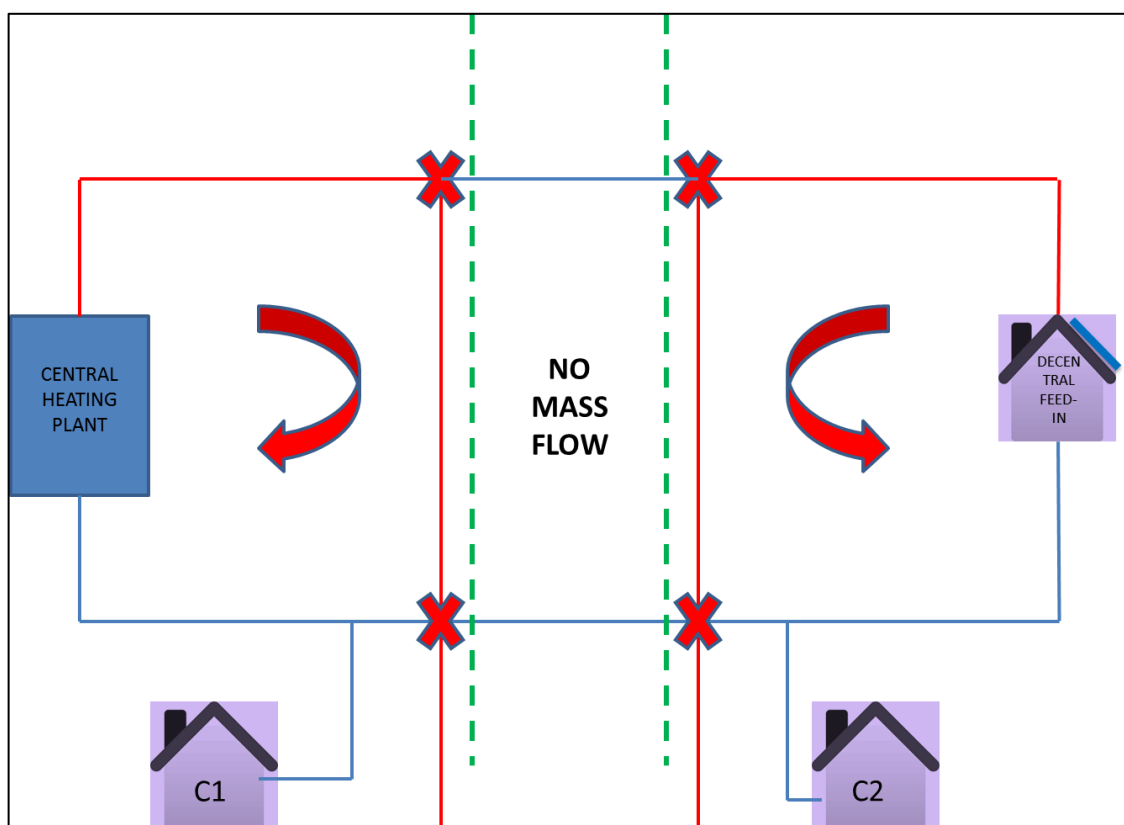


Figure 32: Concept of the district heating network with decentralized heat generators

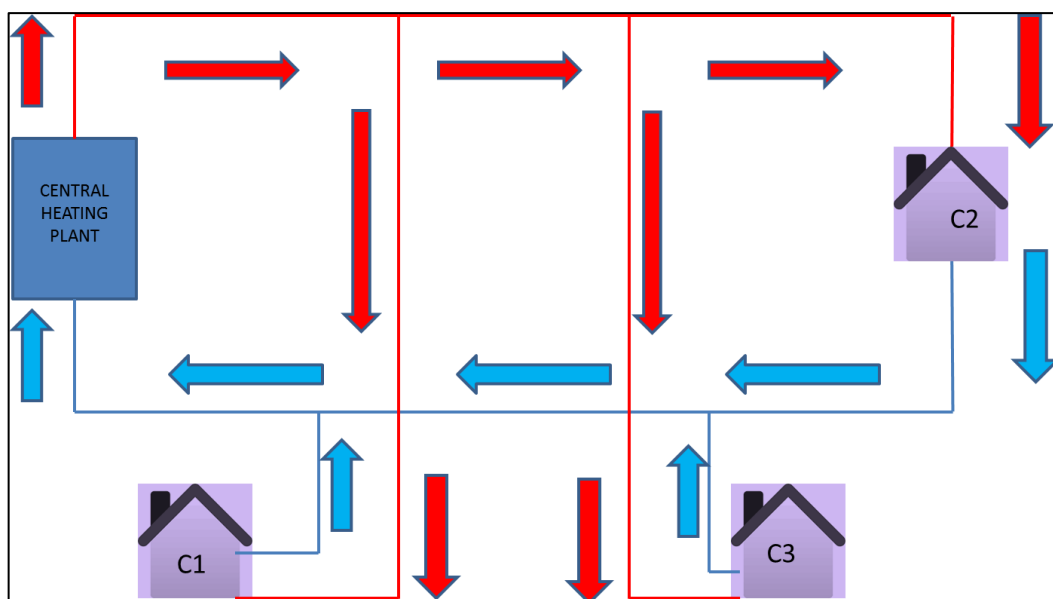


Figure 33: Layout of district heating network without decentralized heat generators

Figure 32 shows the general layout of the district heating network with decentralized heat generation. As it has been earlier discussed the central heating plant is the primary supplier of energy in the district heating network. With the generation of thermal energy from decentralized substations, the amount of work needed to heat the return fluid in the network decreases. This is explained with context to the Figure 33.

The central heating plant provides the required energy for space heating and domestic hot water heating to all three consumers in case of a network without decentralized feed-in. This is shown in Figure 33. In case of a district heating network without decentralized feed-in, there is a forward flow pipe or delivery pipe and a return pipe connecting all the consumers of the network. The red lines in Figure 33 indicate the forward flow pipes to the consumers containing the fluid at a temperature of approximately 80 °C. The blue lines indicate the return flow of the network connected back to the central heating station to form the closed circuit.

The Figure 32 shows a network with three consumers (including one prosumer) and a central heating plant. The prosumer is defined as a consumer that produces and consumes energy. As shown in Figure 32, the consumers are C1 and C2. The prosumer is the building that depicts a solar flat plate collector on the roof. The idea of the use of decentralized heat generators is to decrease the work required to heat the fluid in the central heating plant. This also means that using decentralized heat generators divides the network by the prosumers

feeding energy to the consumers depending on the energy produced by the prosumer in the network. Referring to Figure 32, this implies that when the energy produced by the decentralized heat generator is greater than the energy of the fluid flowing through the district heating network, this building would be capable of feeding the other building with energy. This is clearly represented in Figure 32, where the building with decentralized heat generation delivers heat to the consumer C3 as the energy generated at the decentralized generator is sufficient to feed itself with energy as well as the consumer C3 in the network. The consumer C1 would get the energy for space heating and domestic hot water heating from the central heating plant. Figure 32 shows that with the use of decentralized feed-in, there appears to be two circuits indicated with the red arrows. The consumer is fed by the decentralized heat generator in one and the consumer is fed by the central heating plant in the other. This leads to no mass flow between the green dashed lines as shown in the figure. This is the underlying concept in building the district heating network with decentralized heat generators.

3.3.1 Control strategy of Decentralized feed-in in a District Heating Network

The control of the decentralized feed-in is primarily dependent on the temperature difference between the substation storage and the district heating forward flow. It is switched from the feed from the central heating plant to the decentralized feed-in when the substation temperature is greater than the forward flow temperature which in this case is primarily set to 80 °C.

The change in feed from centralized heating plant to decentralized feed-in is done with the use of a switch block function in Simulink connected in series to the customised Simscape „Flow rate source“ block. The switch block component in Simulink changes the flow from a positive flow to a negative flow depending on the temperature of the substation. This is clearly shown in Figure 34. The „measure_T_surface2“ block measures the temperature of the nodes of the substation storage. The switch block passes through the first input (Decentralized Flow rate, shown in Figure 34) or the third input (Centralized Flow rate, shown in Figure 34) based on the value of the second input. The first and the third inputs are called *data* inputs. The second input is called the *control* input. In this case, the control input is the temperature should be greater than

80 °C for the decentralized feed-in. Under this condition which the switch block passes the first input by using the criteria for passing first input and threshold parameters.

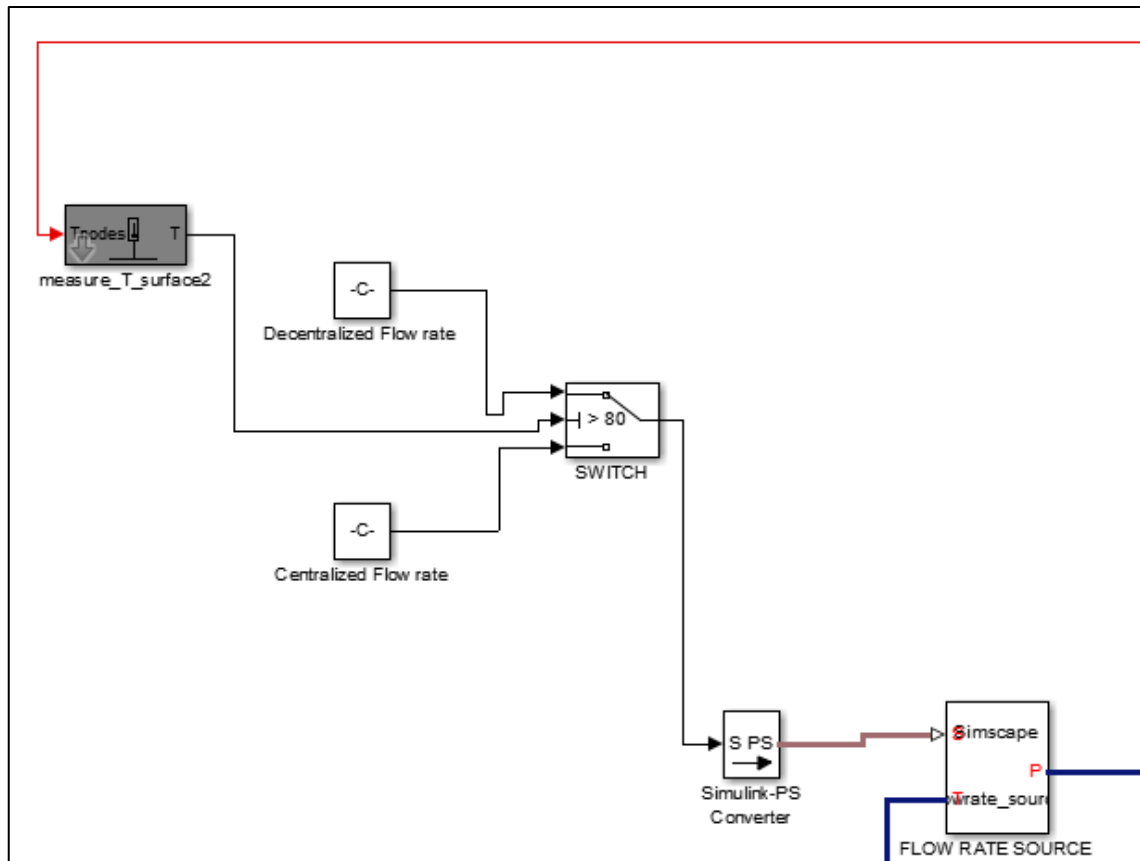


Figure 34: Control strategy of a decentralized feed-in in a district heating network

Thereby, the flow rate source is fed with the flow rate from the „SWITCH“ component block in Simulink through the Simulink-PS converter into the Simscape framework viz the district heating network. By setting a negative flow rate to the flow rate source, the flow of the fluid is set in the opposite direction to the way in which it was previously flowing in. This makes the system bidirectional in nature which could be handled with Simscape components. This can be seen in the nature of flow directions of the fluid in Figures 35 and 36 respectively. Figure 35 shows the direction of the fluid flow during no decentralized feed-in where the consumer is fed with energy from the central heating plant. In Figure 36, due to higher thermal storage temperatures in the consumer substation, the flow direction is reversed which is depicted with the red arrow.

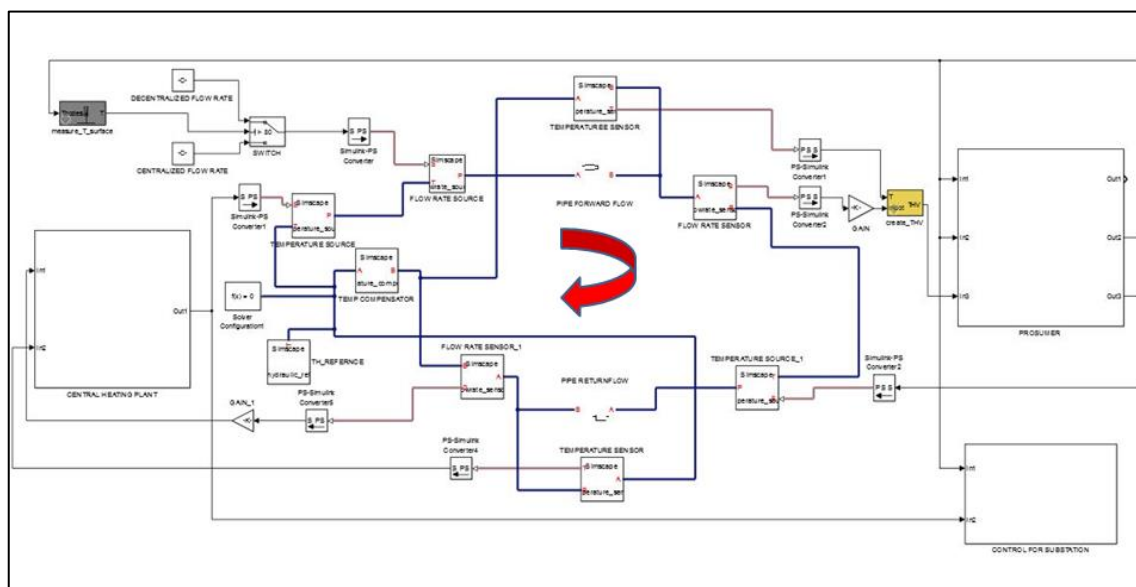


Figure 35: Flow direction without decentralized feed-in in the district heating network

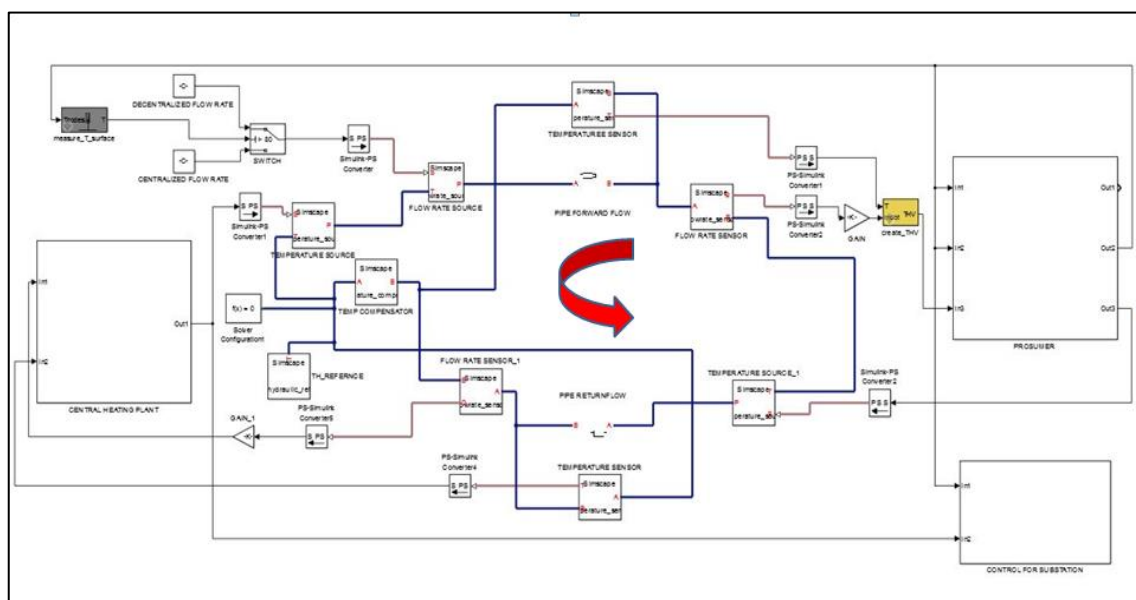


Figure 36: Flow direction with decentralized feed-in in the district heating network

3.3.2 Control Strategy within a Decentralized feed-in Substation

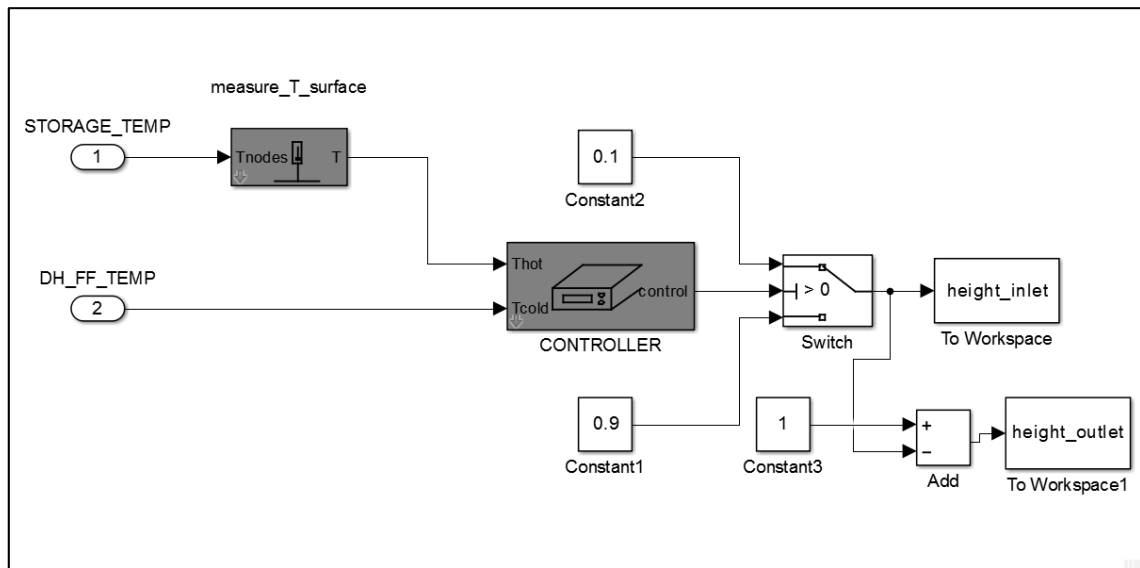


Figure 37: Control for the decentralized feed-in in a consumer substation

The figure 37 shows the control strategy modelled at the decentralized consumer substation. The variables here are the inlet height and the outlet height for the storage modelled in the consumer substation. The consumer substation is explained in detail in Chapter 3.2.4. It has been described in the substation for the consumer in chapter 3.2.4, that energy produced by the decentralized generators is fed. This ensures that the consumers not only use this decentralized energy but also reverses the direction of flow depending on the overall storage temperature as compared to the district heating flow temperature. In order to reverse this flow, the control shown in Figure 37 is modelled.

The inputs to the controller are the storage temperature at the consumer substation (STORAGE_TEMP, shown in Figure 37) and the district heating forward flow temperature (DH_FF_TEMP, shown in Figure 37). Depending on the difference between the storage temperature and district heating forward flow temperature, the control sets the inlet height and the outlet height of the district heating pipe connection to the storage. This implies that if the storage temperature of the consumer substation is greater than the incoming forward flow of the district heating network, the height inlet of the district heating pipe connection to the storage is set at „0.1“ and the outlet at „0.9“ relative to the bottom of the storage of the substation. The vice versa takes place when the storage temperature of the substation is lesser than the forward flow

temperature of the district heating system. This means that „0.9“ is set as the height inlet and „0.1“ as the height outlet relative to the bottom of the storage system.

As the pipe inlet to the storage system for the decentralized feed-in is set at „0.95“ and outlet at „0.05“ respectively throughout. The only changing parameters which are the district heating inlet and outlet pipe connection defines the decentralized feed-in or not.

Chapter 4. Simulation Scenarios

The district heating model with decentralized heat generators in CARNOT and Simscape have been tested under various scenarios. The different scenarios are :

- Scenario 1: Simulation with decentralized renewable energy feed-in using CARNOT block components with a uni-directional flow behaviour.
- Scenario 2: Simulation without decentralized renewable energy feed-in using CARNOT block components.
- Scenario 3: Simulation of the model with decentralized renewable energy feed-in generation using CARNOT and customised Simscape components with a uni-directional flow behaviour.
- Scenario 4: Simulation of the model with decentralized renewable energy feed-in generation using CARNOT and customised Simscape components with a bi-directional flow behaviour.

It is also part of this thesis that the main reasons for comparing scenario's 1 and 3, scenario's 3 and 4 and scenario's 1 and 2 are different from one another. The Scenario's 1 and 2 are compared with one another for the benefits of having renewable energy feed-in in the system. Scenario's 1 and 3 are compared with one another to compare the performance of the system modelled with customised Simscape components in scenario 3 with CARNOT block components in scenario 1. Scenario's 3 and 4 are compared for uni-directional and bi-directional decentralized feed-in flow using customised Simscape components.

4.1 Scenario 1: Simulation with Decentralized Renewable Energy Feed-in using CARNOT Block Components with a uni-directional flow behaviour

A district heating network with a central heating station and a prosumer with a decentralized solar feed-in system is modelled with CARNOT block components in Simulink. This is modelled with components discussed in Chapter 3. The CARNOT components are used to model a system with uni-directional behaviour. The system is modelled in CARNOT so that it can be used to

validate against a system modelled with Simscape and CARNOT components. A model of the same system is shown in Figure 38.

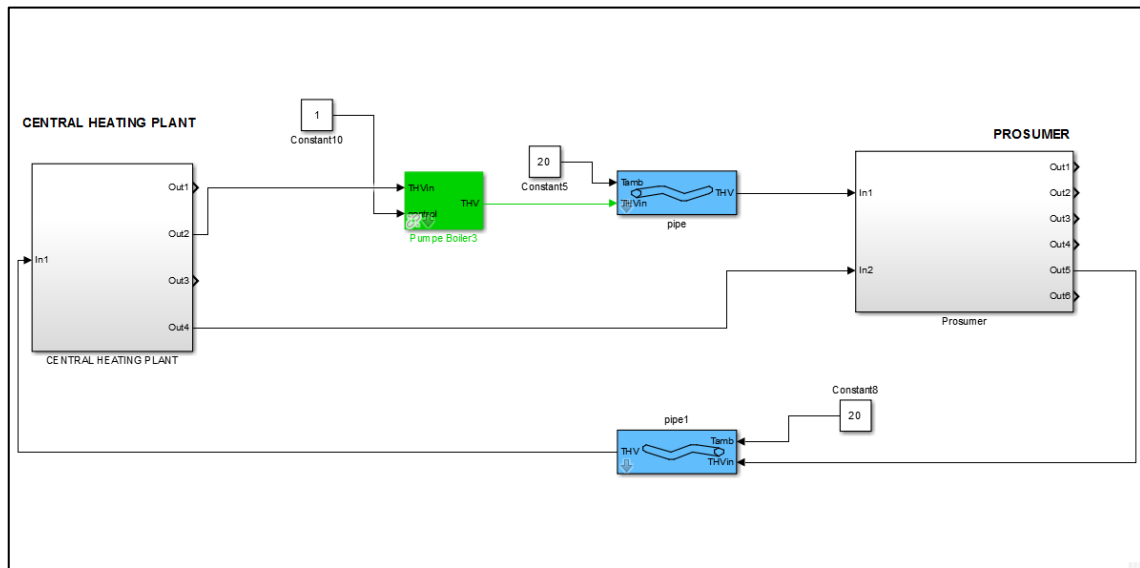


Figure 38: Layout of the district heating network with decentralized heat generators with CARNOT block components

As shown in Figure 38, a central heating plant within the mask with space heating and domestic hot water heating consumption is modelled. The Prosumer also contains the space heating and domestic hot water consumption along with production of decentralized solar energy. The district heating network is modelled with pipes and pumps connected in series between the central heating plant and the prosumers within the network. The system is unidirectional means that the flow temperature of the fluid from the central heating plant is heated with solar energy at times of production at the prosumer's end. This is then fed to the central heating plant through the return flow pipe which makes it uni-directional in nature. The return flow pipe in figure 38 is „*pipe1*“ and the forward flow pipe is depicted as „*pipe*“.

4.1.1 Parameters used for Simulation

The district heating model described in Chapter 4.1 is simulated for a yearly consumption. The parameters for simulation include the solver configuration block parameters in Simulink. This plays a crucial role in the optimization of simulation time. The parameters such as yearly consumption of space heating and domestic hot water heating have been used based on the data described in Chapter 3.2. The weather data used for the simulation is based on longitudinal coordinates -11.45 and latitudinal coordinates 48.77. [28]

A list of the defined parameters used to simulate the scenario discussed in Chapter 4.1 have been enlisted in the table below.

Table 6: List of parameters defined for the simulation of scenario 1, 2, 3 and 4

Parameter	Value	Unit
Mass flow rate of central heating plant pump	4	Kg/s
Mass flow rate of central heating plant domestic water storage pump	0.4	Kg/s
Mass flow rate of central heating plant space heating pump	2	Kg/s
Mass flow rate of District heating network pump	0.4	Kg/s
Diameter of supply and return flow pipes of DH	0.08	m
Length of supply and return flow pipes of DH	50	m
Conductivity of DH Pipe insulation	0.04	W/m.K
Ambient temperature	20	°C
Area of solar collector	100	m ²
Collector slope	15°	[-]
Collector azimuth	90°	[-]
Mass flow rate of prosumer domestic hot water storage pump	0.2	Kg/s
Mass flow rate of prosumer space heating pump	0.2	Kg/s
Mass flow rate of the solar collector pump	3.5	Kg/s

4.1.2 Simulation Results for Scenario 1

The simulation for scenario 1 have been presented in the following sub-chapters 4.1.2.1, 4.1.2.2, 4.1.2.3 and 4.1.2.4.

4.1.2.1. Supply and Return Temperatures in the DH Network

The model is simulated with the parameters discussed in section 4.1.1. The time of simulation is one year. The solver type used in this case is a variable step ode 23 solver (Bogacki-Shampine). The zero crossing events used were based on the local settings specified as default. The relative tolerance specified before the start of the simulation is 0.001. The simulation sample time is 600 seconds.

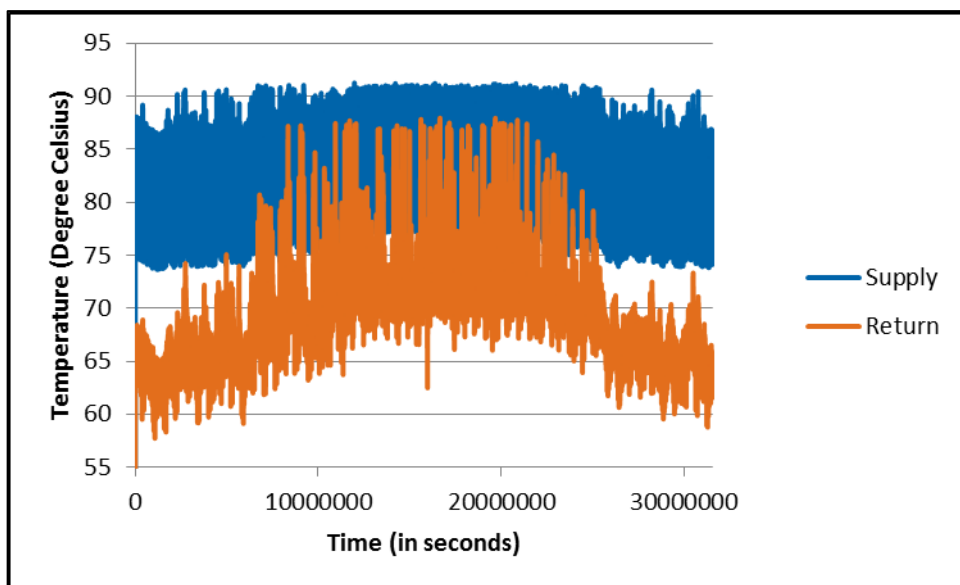


Figure 39: Comparison of return flow versus forward flow temperatures at a constant set flow rate of 0.4kg/s

A comparison of the forward flow temperature against the return flow temperature is shown in Figure 39. The interval between every time step is 600 seconds. The mass flow rate of the fluid through the district heating network is set at a constant value of 0.4 kg/s throughout the simulation.

The results of the simulation in scenario 1 with regard to Figure 39 have been tabulated below:

Table 7: Results of the Simulation for Scenario 1

Statistics	Forward Flow Temperature	Return Flow Temperature
Minimum	73.55°C	53°C
Maximum	91.35°C	87.94°C
Mean	81.37°C	69.14°C
Median	80.46°C	70°C
Range	17.8°C	67.94°C

4.1.2.2. Temperature losses across the district heating network pipes

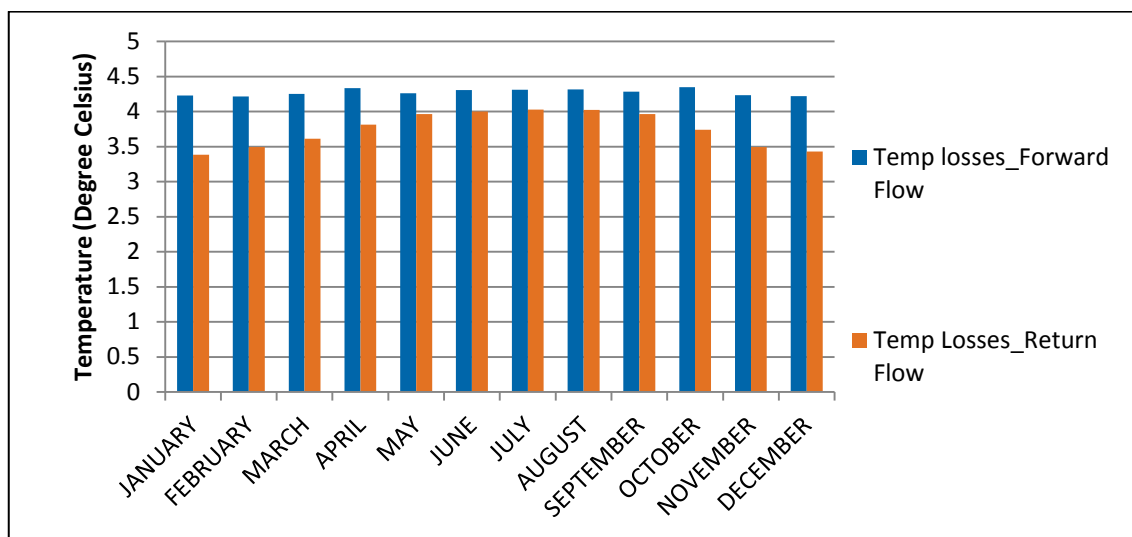


Figure 40: Temperature losses across the district heating network pipes (length = 50 metres)

Figure 40 shows a comparison of the temperature losses across the return flow and the supply pipe in the district heating network. The values are averaged for a period of one month each. The pipe length as discussed earlier in the section on parameters used for simulation is 50 metres each for supply and return pipe. The diameter of the return and of supply pipes are 0.08 metres. Based on figure 40, few statistical comparisons are made in Table 8 which is based on the average monthly supply and return flow temperatures.

Table 8: Results for average monthly temperature losses across supply and return flow pipes in scenario 1

Statistics	Forward flow	Return Flow
Maximum average temperature loss	4.34°C	4.02°C
Minimum average temperature loss	4.21°C	3.38°C
Average temperature losses/ year	4.28°C	3.74°C
Average losses per metre	0.085°C/m	0.074°C/m

4.1.2.3. Decentralized Heat Generator - Solar Collector

The solar flat plate collector with a collector area of 100 m^2 was used during the simulation. Other important parameters such as the optical efficiency and effective heat capacity of collector are set at 80% and $9400 \text{ J/m}^2\text{K}$ respectively during the duration of the simulation. The linear heat loss coefficient (a_1) is set at $3.5 \text{ W/m}^2\text{K}$ and the quadratic heat loss coefficient (a_2) are set at $0.02 \text{ W/m}^2\text{K}^2$. The sample time for the time axis in this case is 600 seconds. Figure 41 shows the total solar irradiation on the surface for the simulation which is based on the weather data vector. The total solar irradiation is the sum of the diffuse radiation and the direct radiation. Figure 42 gives the collector temperatures during the period of the simulation of one year.

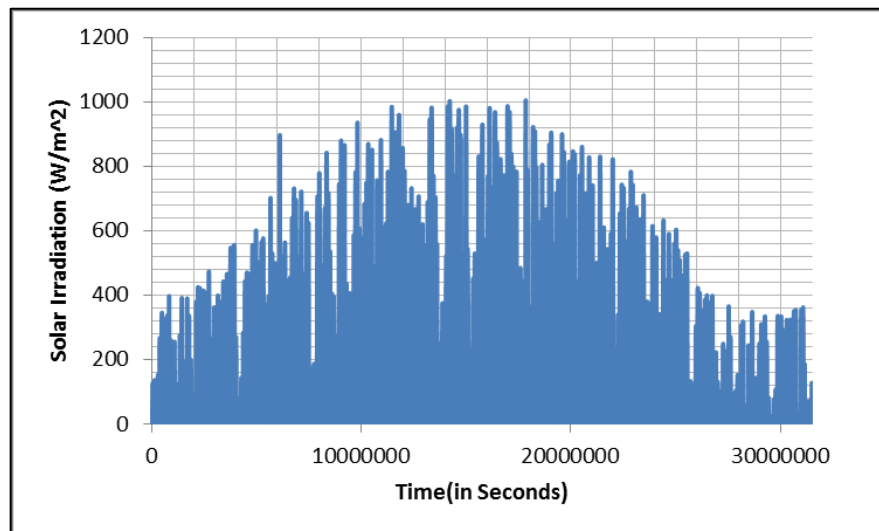


Figure 41: Solar irradiation (W/m^2) on the surface during a period of one year

The solar collector temperature is shown in figure 42. The temperatures range between a maximum of around 160°C to a minimum of approximately -15°C . This is due to the decentralized feed-in. The storage of the consumer substation and the flow rate of the pump for the solar collector are set at 2 m^3 and 3.5 kg/s for this scenario. The pump for the solar collector circulates the fluid depending on the controller signal which is based on the temperature difference between the solar collector and the consumer storage. This is the reason for the high temperatures in the collector temperature diagram showed in figure 42.

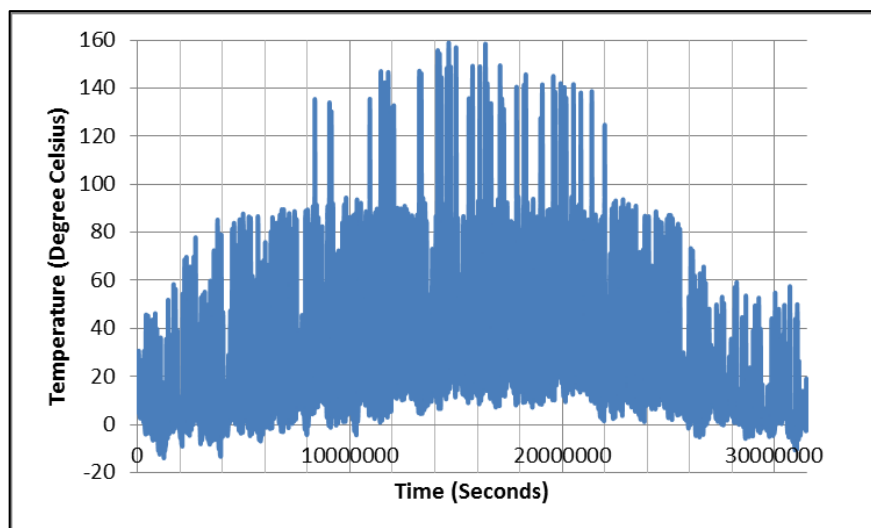


Figure 42: Solar collector temperature during the simulation scenario 1

4.1.2.4 Energy losses across the district heating network

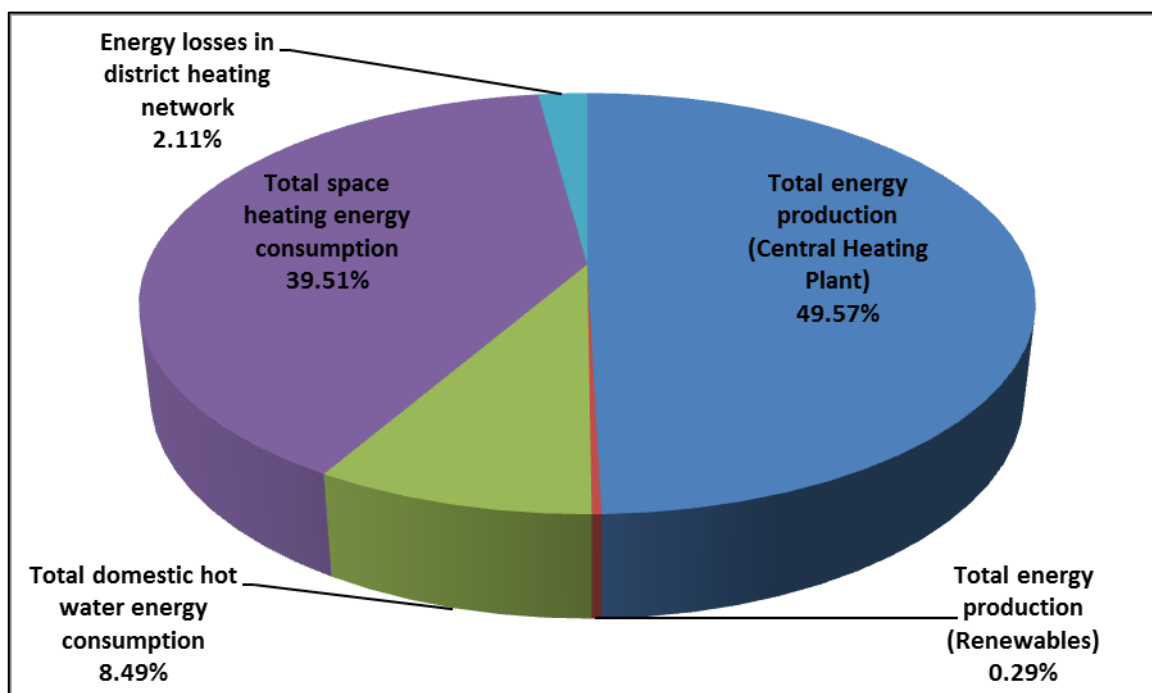


Figure 43: Energy distribution pie chart in a district heating network for Scenario 1

Figure 43 shows the distribution of energy production, consumption and losses in the district heating network modelled in scenario 1. The consumption activities include domestic hot water and space heating at the consumer end. Hot water consumption and space heating in the central heating plant itself is also accounted for. For a production of 49.57% energy from the central heating

plant with primary fossil based generation, 0.29% renewable energy generation at the prosumer's end and a consumption in total of 48% (39.51% from space heating and approximately 8.49% in domestic hot water heating consumption); there is a total energy loss of 2.11% in the district heating piping network. The pipe lengths for the supply and the return flow are 50 metres each in this case.

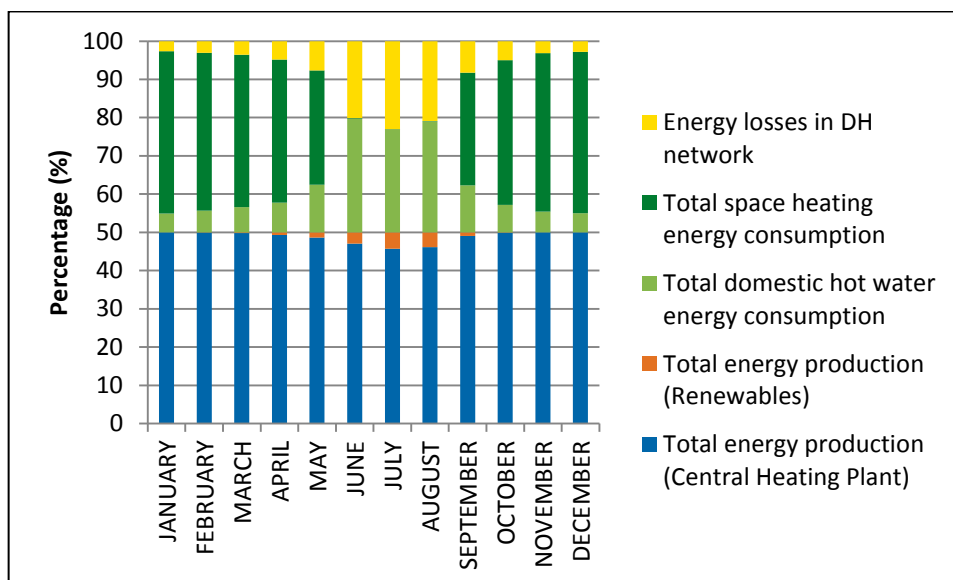


Figure 44: Variation of energy production , consumption and losses over the year for scenario 1

Figure 44 gives an idea of the variation of the energy consumption, production from fossil powered central heating plant and renewables in a district heating network. This gives an impression of the losses of the energy in the district heating network during the year.

4.2 Scenario 2: Simulation of the District Heating Network model without Decentralized Renewable Energy Feed-in using CARNOT Block components

The district heating model discussed in Chapter 3 has been simulated for one year of space heating and domestic hot water consumption for the consumers. The Figure 45 gives a broad overview of the model with CARNOT block components that have been simulated for a period of one year. The Figure 45 consists of a central heating plant with domestic hot water and space heating consumption too. The consumer consists of a substation with space heating and domestic hot water consumption from the storage of the substation. The

consumer and the central heating plant are connected with the supply and return flow pipes with CARNOT „pipe“ block components. This represents the district heating connection in the network. Since there is no decentralized feed of renewable energy in this scenario, the consumer doesn't produce energy in this case. Rather, it is completely dependant on the central heating plant for the consumption of energy.

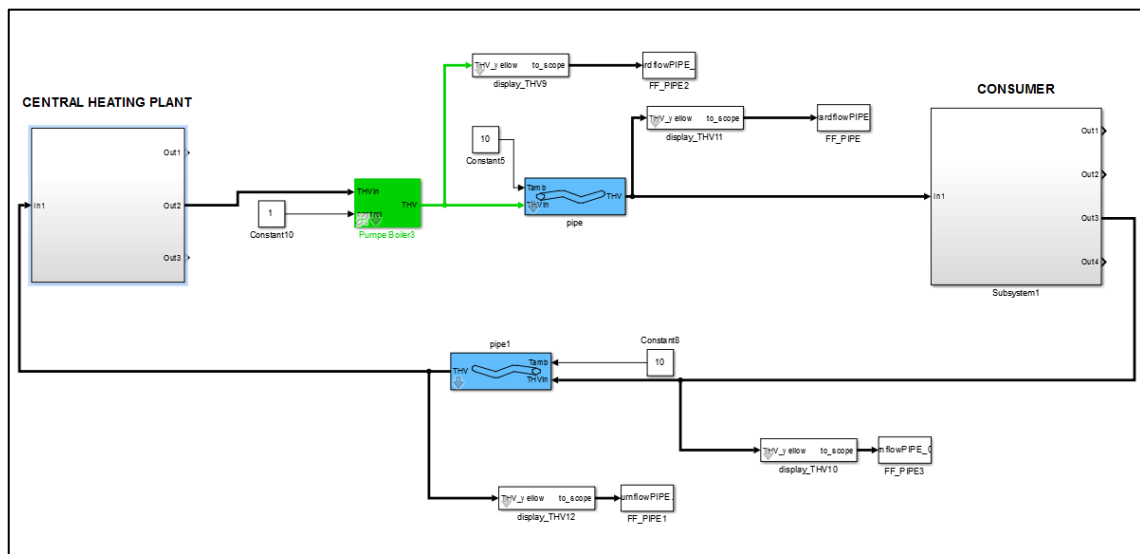


Figure 45: Layout of the district heating network with no decentralized renewable energy feed-in used for simulation in scenario 2

The parameters for the simulation period of one year in this case are the same used for the simulation of scenario 1 as discussed in chapter 4.1.1 (Table 6). The solver used for the simulation is ode23 (Bogacki-Shampine). The solver type is a variable step type with a relative tolerance of 0.01. The sample time for the simulation is 600 seconds.

4.2.1 Simulation Results for Scenario 2

The simulation results for the scenario 2 have been presented in the following sub-chapters 4.2.1.1, 4.2.1.2 and 4.2.1.3.

4.2.1.1 Supply and Return Temperatures in the DH Network

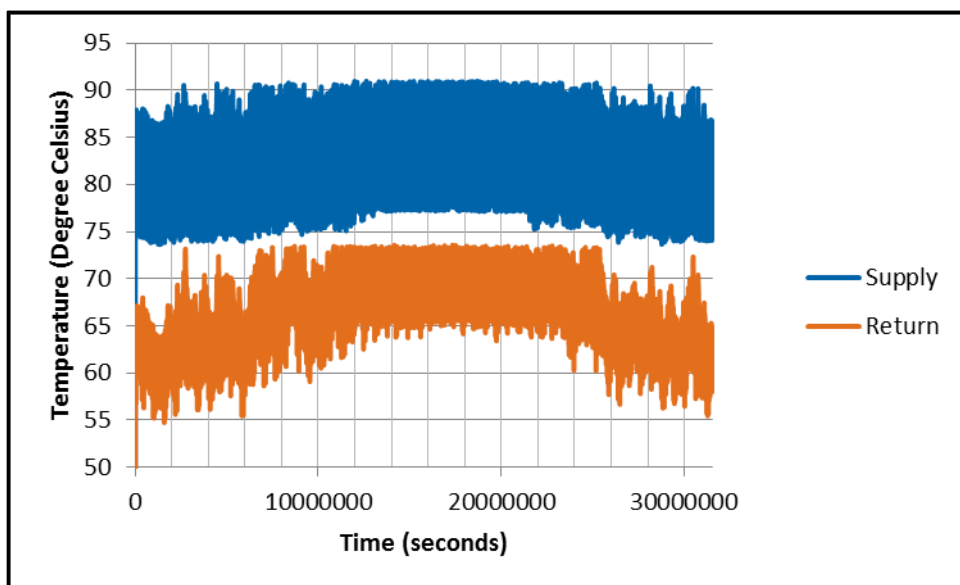


Figure 46: Supply and return flow temperatures for scenario 2 at a constant set mass flow rate = 0.4 kg/s in the district heating network

Figure 46 shows the comparison of the supply and return temperatures of the district heating network modelled for scenario 2. The solver type used in this case is a variable step ode 23 solver. The zero crossing events used were based on the local settings specified as default. The relative tolerance specified before the start of the simulation is 0.001. The simulation sample time is 600 seconds. The mass flow rate is kept constant at 0.4 kg/s for scenario 2. Table 9 gives the statistical results explaining Figure 46.

Table 9: Results of the Simulation for Scenario 2

Statistics	Forward Flow Temperature	Return Flow Temperature
Minimum	73.53°C	49.04°C
Maximum	90.89°C	73.57°C
Mean	81.55°C	67.96°C
Median	81.18°C	68.12°C
Range	70.89°C	53.57°C

4.2.1.2 Temperature losses across the district heating network pipes

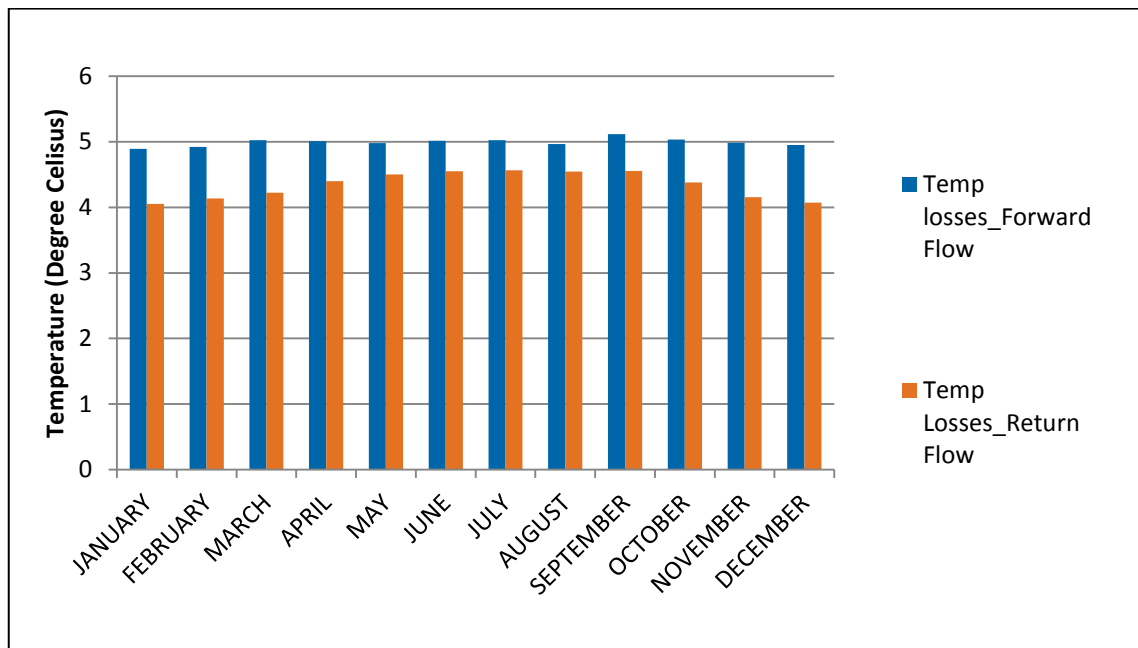


Figure 47: Temperature losses across the district heating network supply and return pipes (each with a pipe length = 50 metres)

Figure 47 shows a comparison of the temperature losses across the return flow and the supply pipe in the district heating network. The values are averaged for a period of one month each. The pipe length as discussed earlier in the section on parameters used for simulation is 50 metres each for supply and return pipe. The diameter of the return and of supply pipes are 0.08 metres. Based on figure 47, few statistical comparisons are made in Table 10 based on the average monthly supply and return flow temperatures.

Table 10: Results for the average monthly temperature losses across the supply and return pipe in scenario 2

Statistics	Forward flow	Return Flow
Maximum avg. temperature loss	5.119 °C	4.564 °C
Minimum average temperature loss	4.893 °C	4.052 °C
Average temperature losses/ year	4.994 °C	4.345 °C
Average losses per metre	0.099 °C/m	0.086 °C/m

4.2.1.3 Energy losses across the district heating network

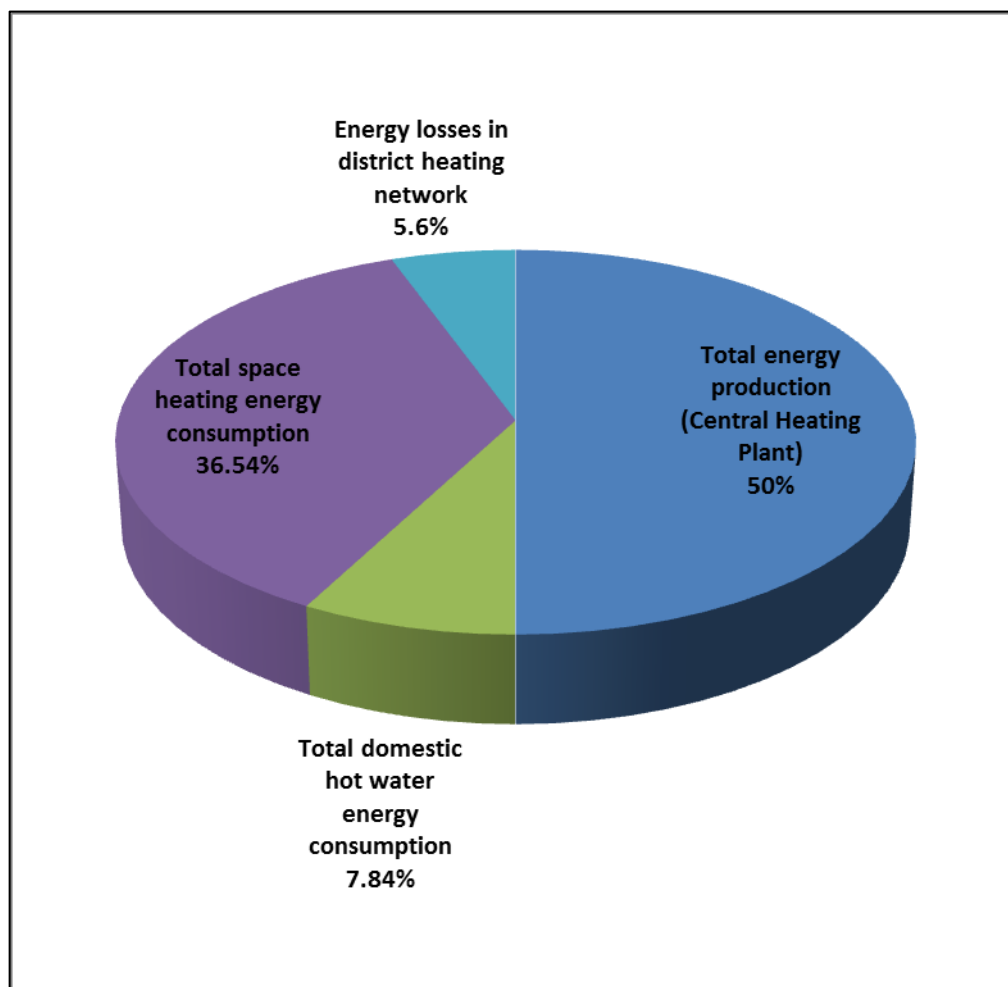


Figure 48: Energy distribution pie chart in a district heating network for Scenario 2

The Figure 48 shows distribution of energy production, consumption and losses in the district heating network modelled in scenario 2. The consumption activities include domestic hot water and space heating at the consumer end. Hot water consumption and space heating in the central heating plant itself is taken into consideration. For a production of 50% energy from the central heating plant with primary fossil based generation and a consumption in total of 44% (36.54% from space heating and 7.84% in domestic hot water heating consumption); there is a total energy loss of approximately 5.6% in the district heating piping network. The pipe lengths for the supply and the return flow are 50 metres each in this case.

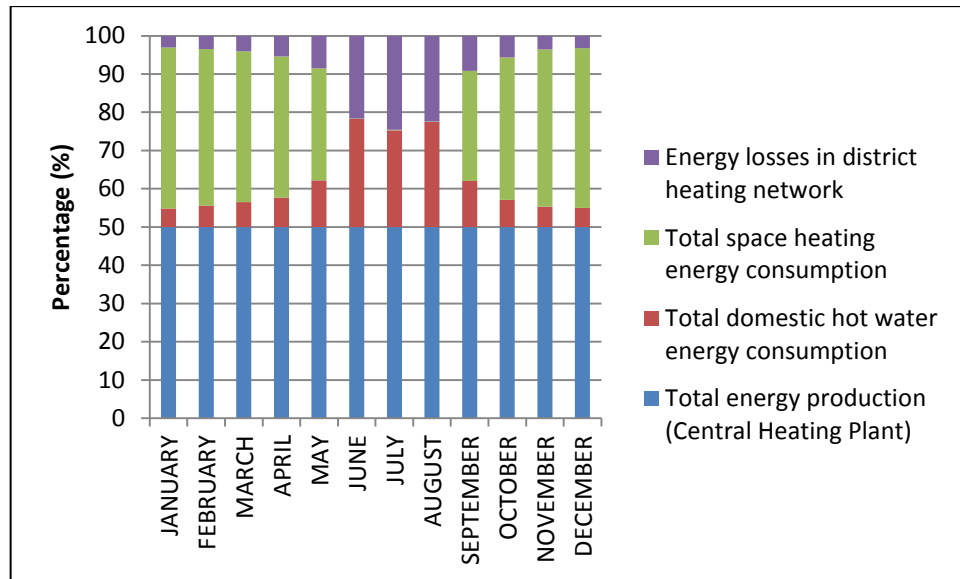


Figure 49: Variation of energy production , consumption and losses over the year in scenario 2

Figure 49 gives an idea of the variation of the energy consumption, production from fossil powered central heating plant in a district heating network. This gives an impression of the losses of the energy in the district heating network during the period of one year.

4.3 Scenario 3: Simulation of the District Heating Network Model with Decentralized Renewable Energy Feed-in generation using CARNOT and customised Simscape components with a unidirectional flow behaviour

In scenario 3, a district heating network with a central heating station and a prosumer with a decentralized solar feed-in system is modelled with CARNOT blocks and customised Simscape components. This is modelled with the components discussed in Chapter 3. The central heating station and the prosumer in the network are modelled with CARNOT block components. The district heating network supply and return pipes are modelled with customised Simscape components. The CARNOT components are used to model a system with uni-directional behaviour. The Simscape components are used in order to model a bi-directional behaviour in the system. Figure 50 shows the description of the model for the simulation scenario 3.

The solver used for the simulation is a variable step type ode 23 (Bogacki-Shampine) solver. The solver is compatible for the CARNOT components in Simulink. The relative tolerance is set at 0.01 for the duration of the simulation. Within the solver configuration block in Simscape, the consistency tolerance is set to 1. The solver used for Simscape is the local solver with solver type-Backward Euler. The zero crossing events used were based on the local settings specified as default. The sample time of the simulation is 600 seconds. The parameters for the simulation period of one year in this case are the same used for the simulation of scenario 1 as discussed in chapter 4.1.1 (Table 6).

The simulation for scenario 3 has a time duration of one year. The results of this scenario have been discussed in sections 4.3.1.1, 4.3.1.2 and 4.3.1.3.

A comparison of the forward flow temperature against the return flow temperature on a monthly average is shown in Figure 51. The mass flow rate of the fluid through the district heating network is set at a constant value of 0.4 kg/s throughout the simulation.

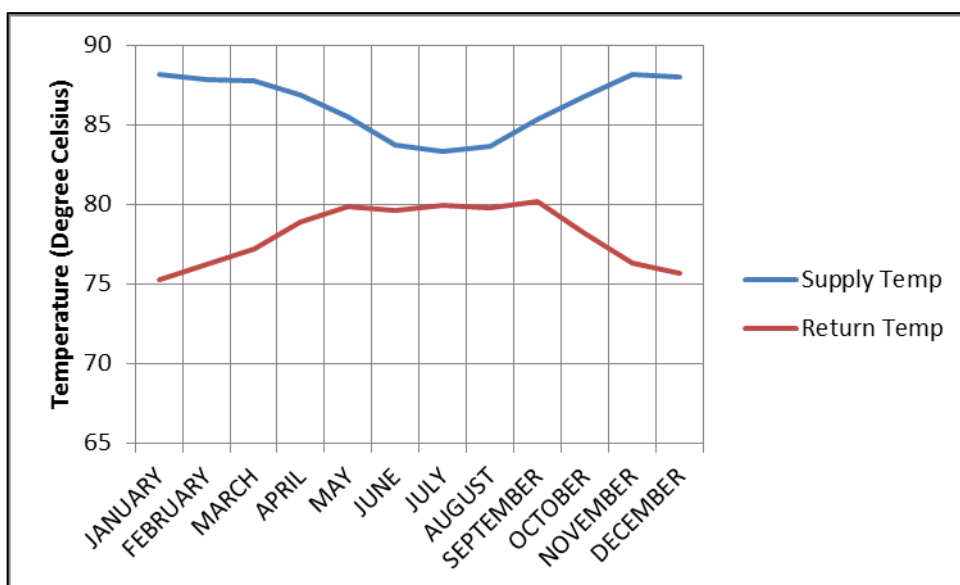


Figure 51: Monthly average supply and return flow temperatures for scenario 3 at a constant set mass flow rate = 0.4 kg/s in the district heating network

The results of the simulation in scenario 3 with regard to the simulation period of one year are tabulated in table 11. These values are based on the 10 minute sample time of supply and return flow.

Table 11: Results of the Simulation for Scenario 3

Statistics	Forward Flow Temperature	Return Flow Temperature
Minimum	75.96°C	65.92°C
Maximum	111.4°C	93.7°C
Mean	86°C	81.42°C
Median	82.9°C	81.69°C
Range	35.39°C	27.78°C

4.3.1.2 Temperature losses across the district heating network pipes

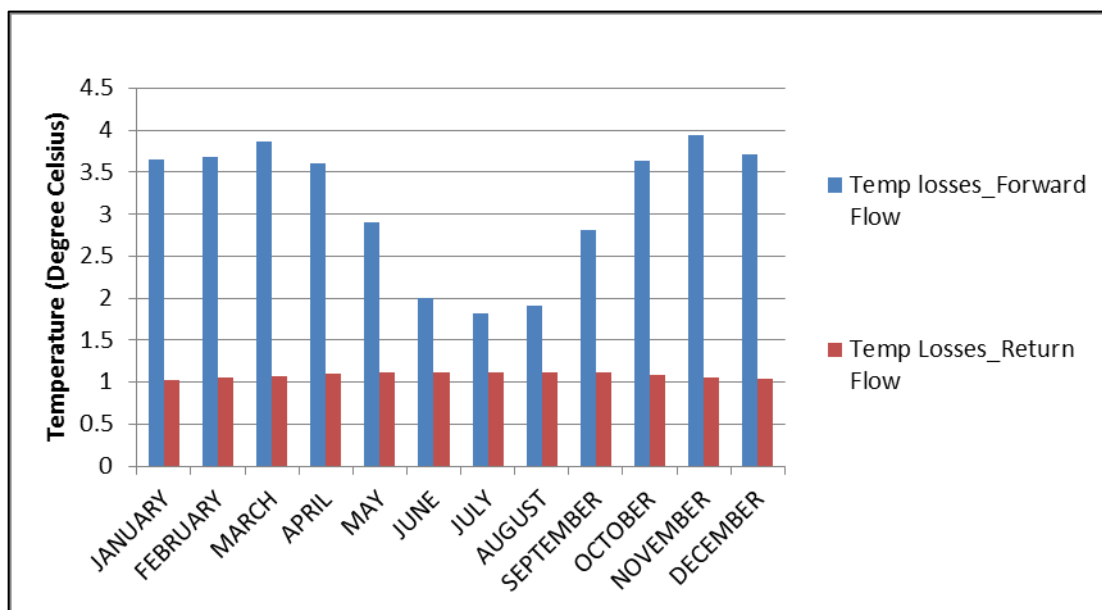


Figure 52: Temperature losses across the district heating network pipes (length = 50 metres)

Figure 52 shows a comparison of the temperature losses across the return flow and the supply pipe in the district heating network. The values are averaged for a period of one month each. The pipe length is 50 metres each for the supply and the return pipe. The diameter of the return and of supply pipes are 0.08 metres. Based on figure 52, few statistical comparisons are made in Table 11 based on the average monthly supply and return flow temperatures.

Table 12: Results for average monthly temperature losses across supply and return flow pipes in scenario 3

Statistics	Forward flow	Return Flow
Maximum average temperature loss	3.93°C	1.122°C
Minimum average temperature loss	1.81°C	1.030°C
Average temperature losses/ year	3.12°C	1.084°C
Average losses per metre	0.062 °C/m	0.021 °C/m

4.3.1.3 Energy losses across the district heating network

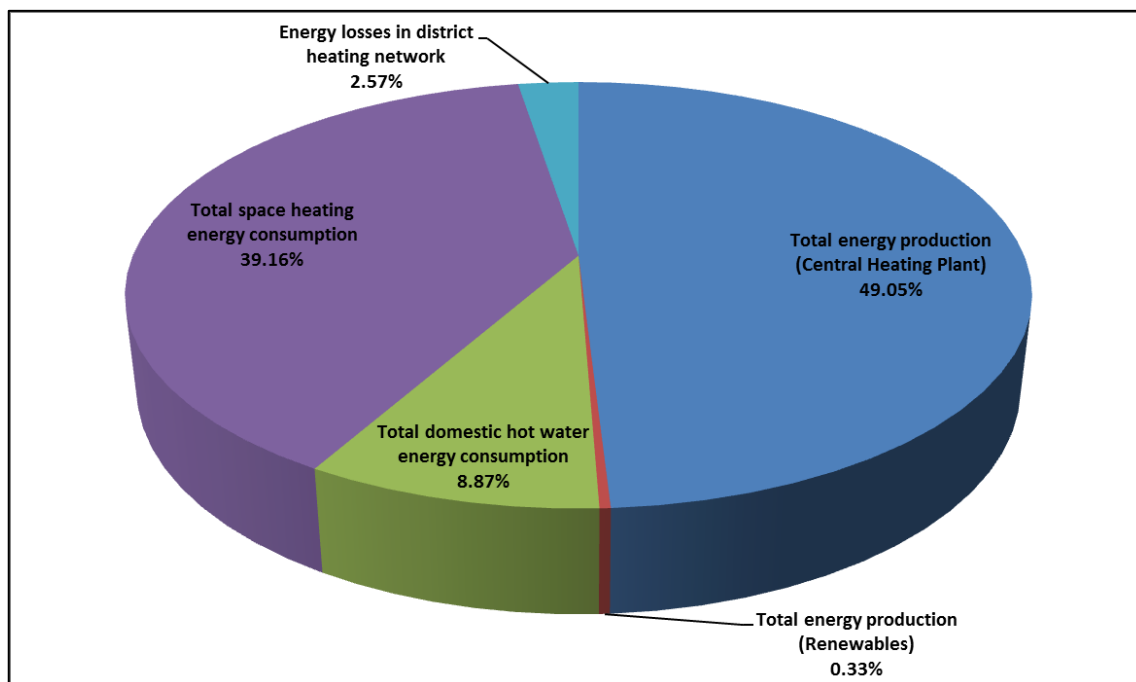


Figure 53: Energy distribution pie chart in a district heating network for Scenario 3

Figure 53 shows the distribution of energy production, consumption and losses in the district heating network simulated in scenario 3. The consumption activities include domestic hot water and space heating at the consumer end. Hot water consumption and space heating in the central heating plant itself is also accounted for. For a production of 49.05% energy from the central heating plant with primary fossil based generation, 0.33% renewable energy generation at the prosumer's end and a consumption in total of 48.03% (39.16% from space heating and 8.87% in domestic hot water heating consumption); there is a total energy loss of approximately 2.57% in the district heating piping network.

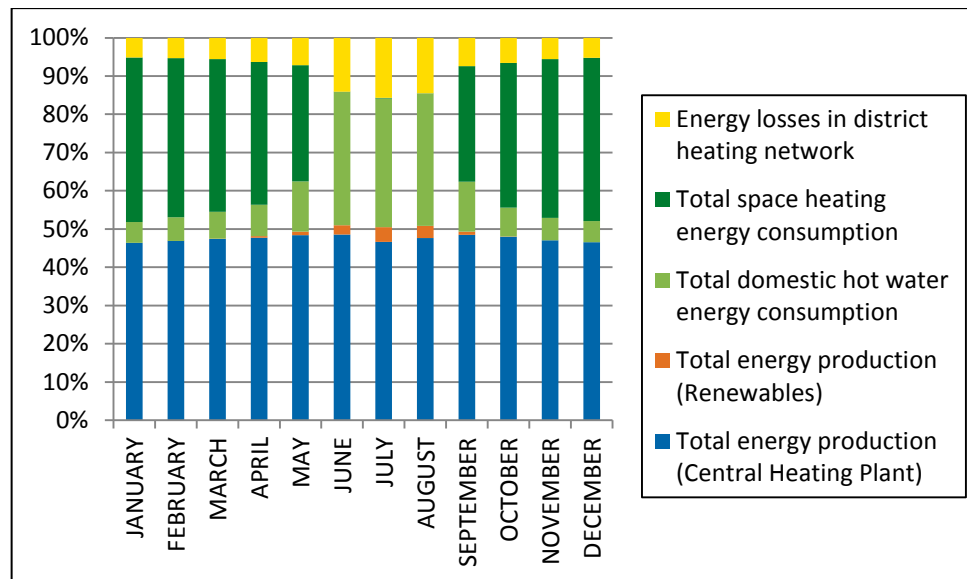


Figure 54: Energy production, consumption and losses over the year in scenario 3

Figure 54 gives an idea of the variation of the energy consumption, production from fossil powered central heating plant and renewables in a district heating network. This gives an impression of the losses of the energy in the district heating network during the duration of the year for scenario 3.

4.4 Scenario 4: Simulation of the District Heating Network Model with Decentralized Renewable Energy Feed-in generation using CARNOT and customised Simscape components with a bi-directional flow behaviour

In scenario 4, a district heating network with a central heating station and a prosumer with a decentralized solar feed-in system is modelled with CARNOT blocks and customised Simscape components. This is modelled with the components discussed in Chapter 3. The difference between this scenario and scenario 3, is that, this scenario is a bi-directional flow behaviour as compared to uni-directional flow in scenario 3. The central heating station and the prosumer in the network are modelled with CARNOT block components. The district heating network supply and return pipes are modelled with customised Simscape components. The CARNOT components are used to model a system with uni-directional behaviour. The Simscape components are used in order to model a bi-directional behaviour in the system. Figure 55 shows the description

of the model for the simulation scenario 4. The control to the flow rate source in Simscape changes between -0.4 kg/s to 0.4 kg/s in the district heating network depending on decentralized generation or not respectively. This makes the system behave in a bidirectional in flow.

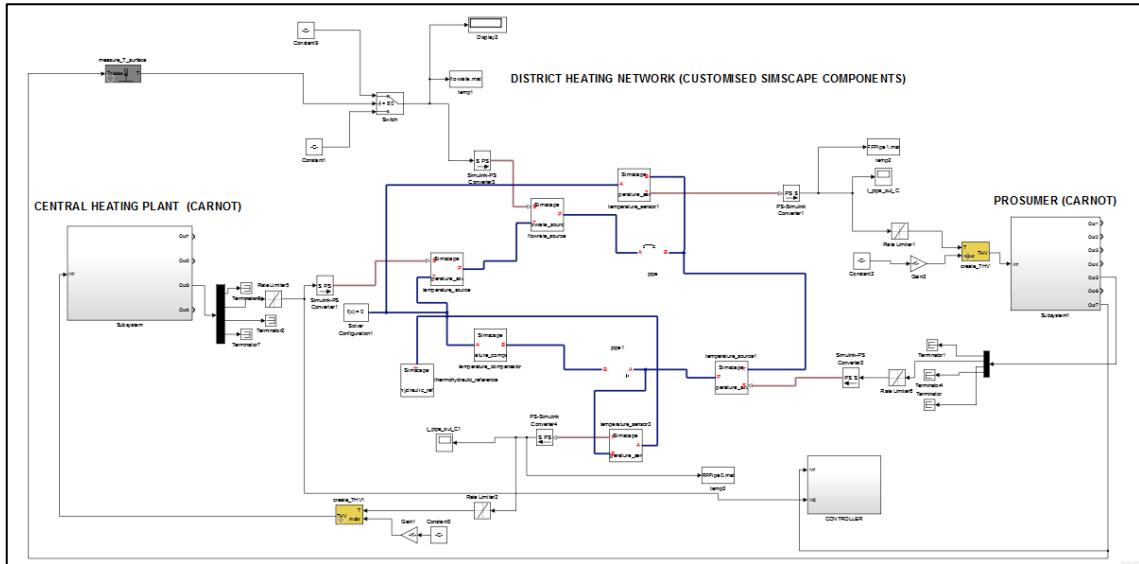


Figure 55: Layout of the simulation model for scenario 4

The solver used for the simulation is a variable step type ode 23 (Bogacki-Shampine) solver. The solver is compatible for the CARNOT components in Simulink. The relative tolerance is set at 0.01 for the duration of the simulation. Within the solver configuration block in Simscape, the consistency tolerance is set to 1. The solver used for Simscape is the local solver with solver type-Backward Euler. The zero crossing events used were based on the local settings specified as default. The sample time of the simulation is 600 seconds. The parameters for the simulation period of one year in this case are the same used for the simulation of scenario 1 as discussed in chapter 4.1.1 (Table 6).

4.4.1 Simulation Results for Scenario 4

The simulation for scenario 4 has a time duration of one year. The results of this scenario have been discussed in sections 4.4.1.1, 4.4.1.2 and 4.4.1.3.

4.4.1.1 Supply and return temperatures in the district heating network

A comparison of the forward flow temperature against the return flow temperature is shown in Figure 56. The interval between every time step is 600 seconds.

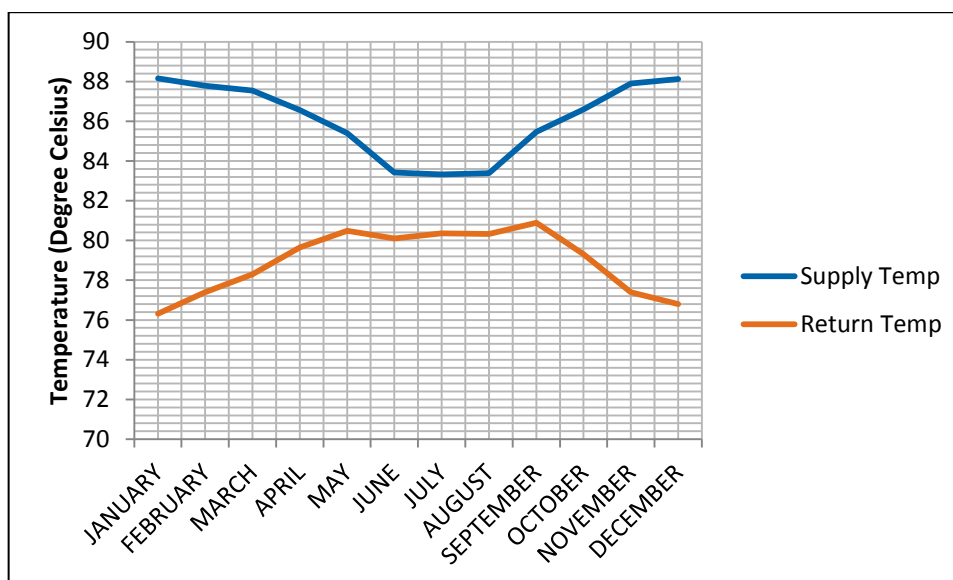


Figure 56: Monthly average supply and return flow temperatures for scenario 4 in the district heating network

The results of the simulation in scenario 4 with regard for the simulation period of one year is tabulated in table 13. These values are based on the 10 minute sample time of supply and return flow

Table 13: Results of the Simulation for Scenario 4

Statistics	Forward Flow Temperature	Return Flow Temperature
Minimum	75.96°C	65.92°C
Maximum	111.4°C	93.7°C
Mean	86.14°C	81.29°C
Median	82.97°C	81.54°C
Range	35.39°C	27.78°C

4.4.1.2 Temperature losses across the district heating network pipes

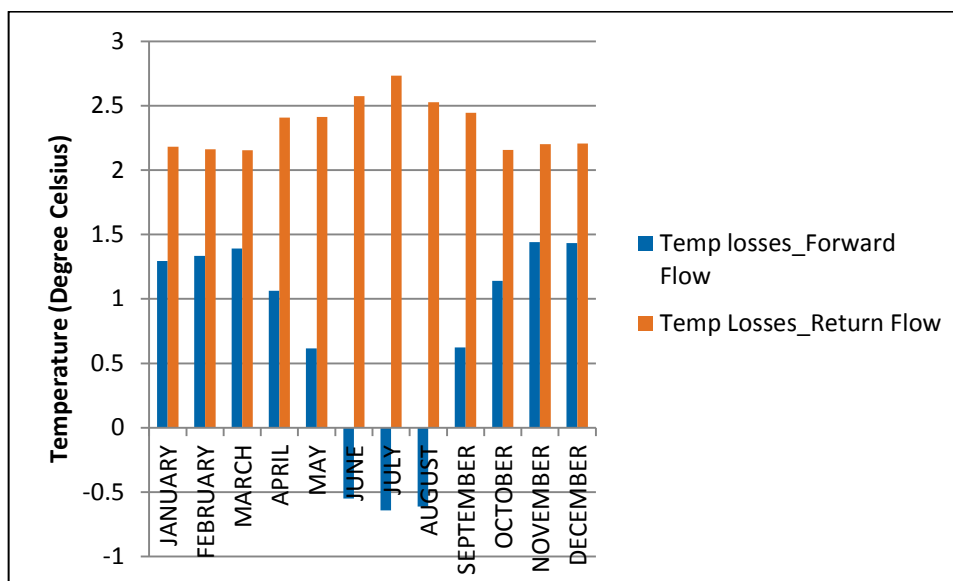


Figure 57: Temperature losses across the district heating network pipes

Figure 57 shows a comparison of the temperature losses across the return flow and the supply pipe in the district heating network. The values are averaged for a period of one month each. The pipe length is 50 metres each for the supply and the return pipe. The diameter of the return and of supply pipes are 0.08 metres. Based on figure 57, few statistical comparisons are made in Table 14 based on the average monthly supply and return flow temperatures.

Table 14: Results for average monthly temperature losses across supply and return flow pipes in scenario 4

Statistics	Forward flow	Return Flow
Maximum average temperature loss	1.4412°C	2.7325°C
Minimum average temperature loss	-0.6421°C	2.1548°C
Average temperature losses/ year	0.7113°C	2.3467°C
Average losses per metre	0.0142°C/m	0.046 °C/m

4.4.1.3 Energy losses across the district heating network

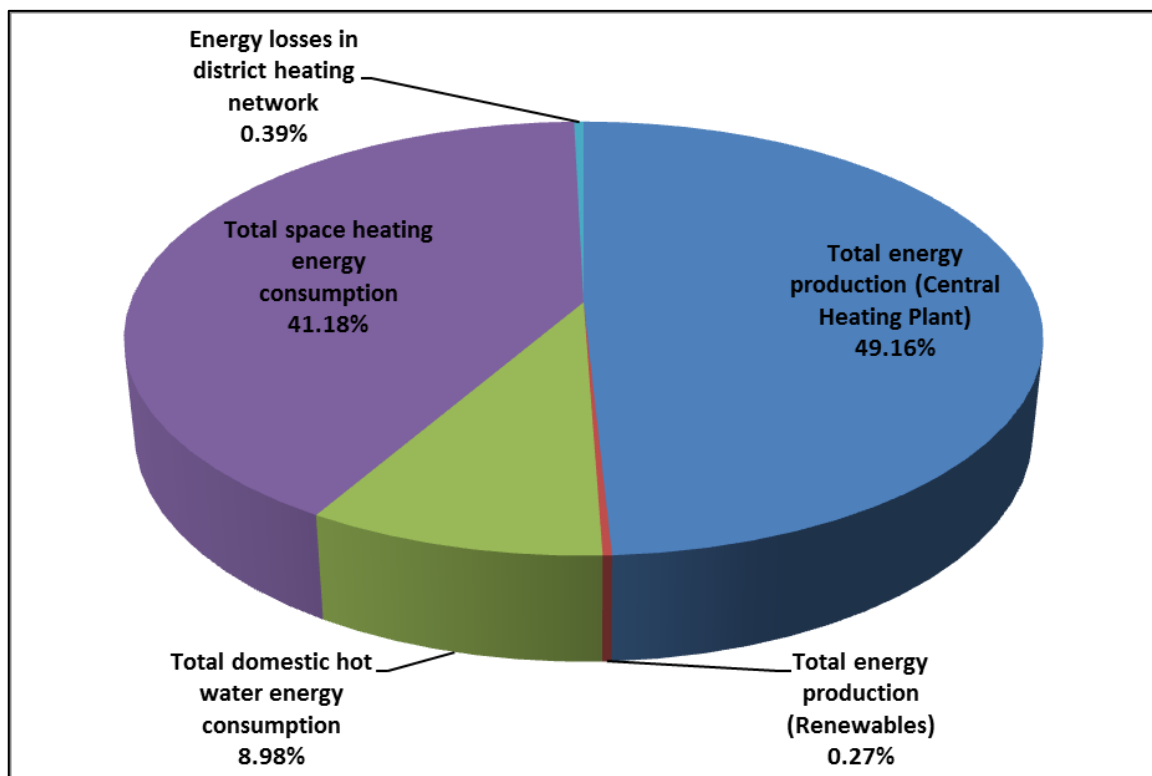


Figure 58: Energy distribution pie chart in a district heating network for Scenario 4

Figure 58 shows the distribution of energy production, consumption and losses in the district heating network simulated in scenario 4. The consumption activities include domestic hot water and space heating at the consumer end. Hot water consumption and space heating in the central heating plant itself is also accounted for. For a production of approximately 49.16% energy from the central heating plant with primary fossil based generation, 0.27% renewable energy generation at the prosumer's end and a consumption in total of approximately 50% (41.18% from space heating and approximately 9% in domestic hot water heating consumption); there is a total energy loss of approximately 0.39% in the district heating piping network.

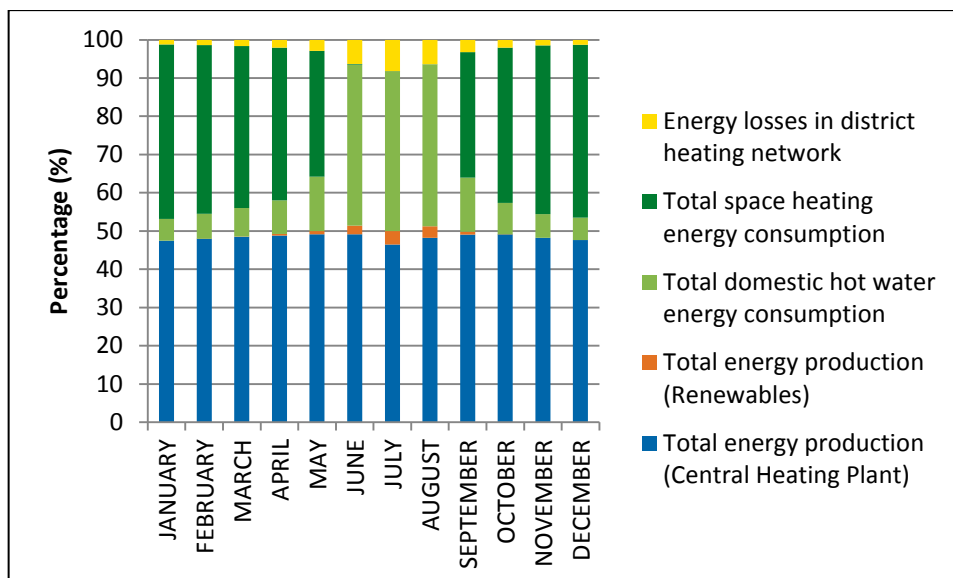


Figure 59: Energy production, consumption and losses over the year in scenario 4

Figure 59 gives an idea of the variation of the energy consumption, production from fossil powered central heating plant and renewables in a district heating network. This gives an impression of the losses of the energy in the district heating network during the duration of the year for scenario 4.

Chapter 5. Evaluation of Results

The results of the simulation scenarios 1, 3 and 4 discussed in Chapter 4 have been explained in detail within this chapter.

5.1 Discussion of results between Scenario's 1 and 3

Scenario 1 as explained earlier in chapter 4 is the district heating model with decentralized heat generators built with CARNOT block components. The solver configuration is the ode 23 variable step type solver.

Scenario 3 is the system built with CARNOT block components for the prosumer's and the central heating plant. The district heating network pipes and flow rate source have been modelled using customised Simscape components. The solver configuration used for the Simscape components is the local solver type. The set sample time for this scenario is 10. The main purpose in this section is to compare the results between the two scenarios, one with decentralized renewable energy solar production and the other with a unidirectional flow.

5.1.1 Energy losses in the district heating network

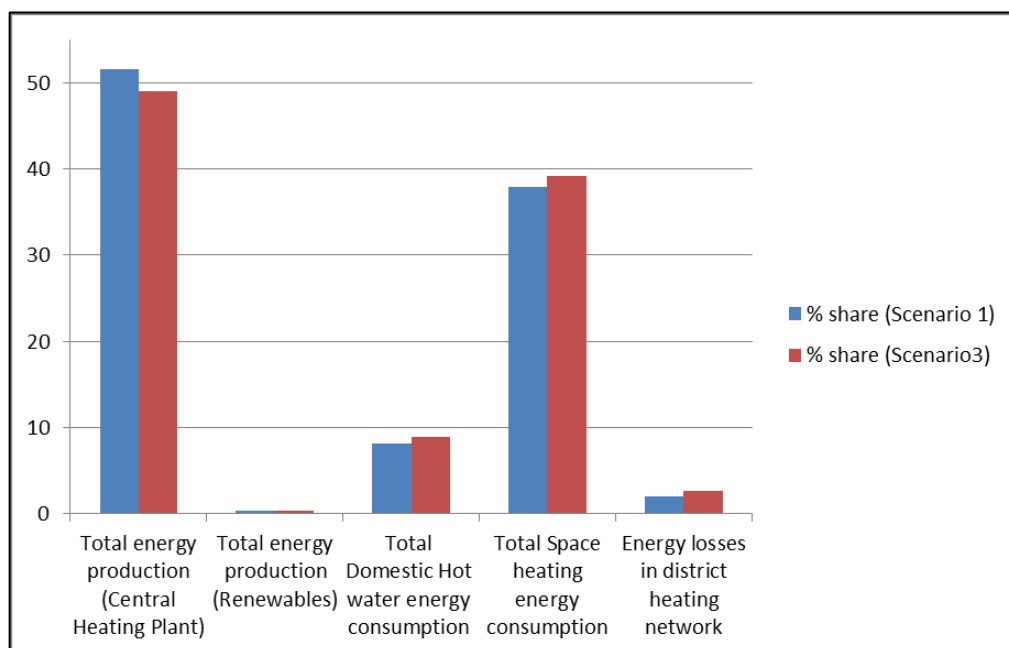


Figure 60: Comparison of energy production, consumption and losses between scenario's 1, 3

The figure 60 depicts the differences in percentage of energy production, consumption and losses in the district heating network for scenario 1 and 3. Figure 60 shows that the results between the two scenario's are similar with regards to total energy production from the central heating plant, renewable energy production and consumption. It is observed that the energy losses across the district heating network are not exactly the same for the two scenario's. The percentage share of energy losses is slightly higher for scenario 3 as compared to scenario 1. The energy losses for scenario 1 is approximately 2.11% and that for scenario 3 is approximately at 2.57%. It is seen from Chapter 4 for scenario's 1 and 3 that the average temperature losses per metre per year for scenario 3 are more as compared to scenario 1. This justifies the difference in the energy losses between the two scenario's. Since the energy losses in the district heating network occur from the pipes in the network, this is a valid point of discussion as the main difference between the two scenario's is the district piping network. There is a difference of almost 17% in energy losses of scenario 1 as compared to scenario 3. The percentage error in energy losses between scenario 1 and 3 have been calculated based on the mathematical formula given as:

$$\% \text{ error in energy losses} = \frac{\text{Energy loss}_{\text{CARNOT}} - \text{Energy loss}_{\text{Simscape}}}{\text{Energy loss}_{\text{CARNOT}}}$$

Based on the above formulation, the percentage error in the district heating network between Scenario 1 and 3 is approximately 22%. This difference in percentage error is due to the customised components in scenario 3. The absolute error for the temperature differences of the customised Simscape components compared to a CARNOT pipe components is of the order 15-20% for a 50 metre length pipe. This has been validated earlier in chapter 2. The rest of the model stays the same in the two scenario's. The other probable reasons for this difference could be the dependancy of specific heat capacity of water as a function of temperature which is not considered.

5.1.2 Supply and return flow temperatures in the district heating network

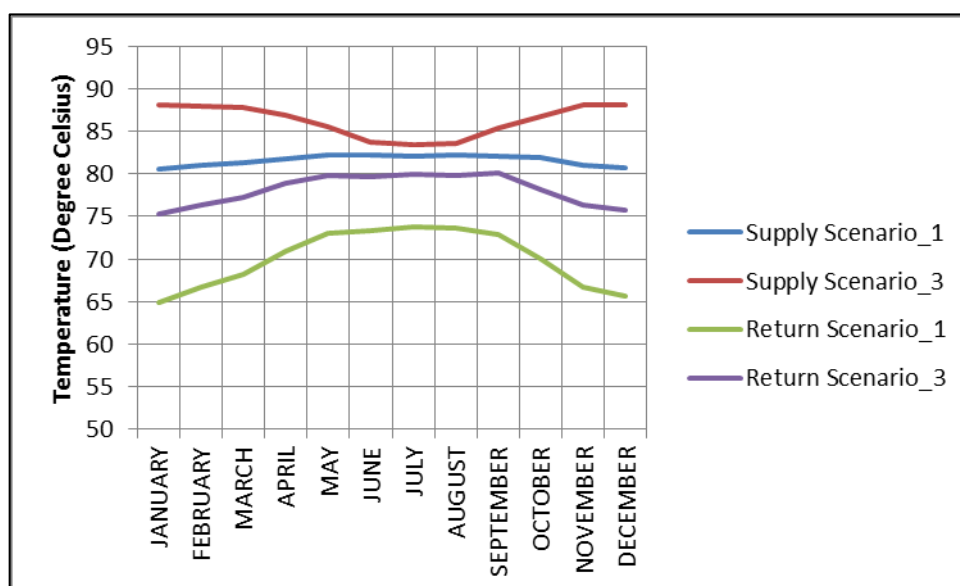


Figure 61: Supply and return temperatures for scenario's 1 and 3

The figure 61 compares the temperatures of the supply and return temperatures of the district heating network for scenario's 1 and 3. Figure 61 gives the monthly average temperatures of supply and return flow temperatures of the flow in the district heating network. The return temperatures are different from one another for the two scenario's at every time during the year for the two scenario's. The same implies for the supply temperatures. The return temperature's for scenario 1 are offset from the return temperature's for scenario 3. This explains the low temperature losses for the customised Simscape components as compared to the CARNOT pipe components for a length of 50 metres in this case.

During the month's of May to August where the solar irradiation is higher, a deviation of behaviour is found between the two scenario's. There is a trough for the supply temperatures for scenario 3 during this period of time. A more flat curve is observed for the supply flow in scenario 1. Simultaneously a crest for the return flow temperature's during the same period of time for scenario's 1 and 3 are observed.

It is observed that there is a higher temperature difference between the supply and return temperature for scenario 1. A lower temperature difference is

observed for the temperature difference between supply and return flow in scenario 3.

The scenario 3 consists of customised Simscape return pipe blocks. This is the main reason for the difference between the temperature difference for the supply and return flow in scenario 3 as compared to scenario 1. In scenario 1, the return flow pipe has been modelled using CARNOT block components.

Table 15 lists the statistics of supply and return temperatures for the two scenarios and thereby gives an explanation to the temperature offset for the supply and return flow in scenario 3 as compared to scenario 1.

Table 15: Comparison between supply and return flow temperatures in Scenario 1 and 3

Statistics	Return flow (Scenario 1)	Return Flow (Scenario 3)	SupplyFlow (Scenario 1)	Supply Flow (Scenario 3)
Maximum temperature	76.31°C	92.21°C	90.92°C	111.62°C
Minimum temperature	43.67°C	62.87°C	72.45°C	75.62°C
Average temperature / year	60.77°C	78.09°C	81.39°C	86.25°C

As seen from Table 15, there is a deviation in the supply and return flow temperatures for the two scenarios discussed. It is therefore necessary to understand the percentage of deviation between the two scenarios discussed.

Since , scenario 3 consists of the customised Simscape components and scenario 1 with CARNOT components, a mathematical formula calculating the deviation of scenario 3 with scenario 1 is shown as follows:

$$deviation = \frac{T_{scenario\ 3,x} - T_{scenario1,x}}{T_{scenario\ 1,x}}$$

Where, x is a parameter which in this case is the maximum temperature, minimum temperature or average temperature per year.

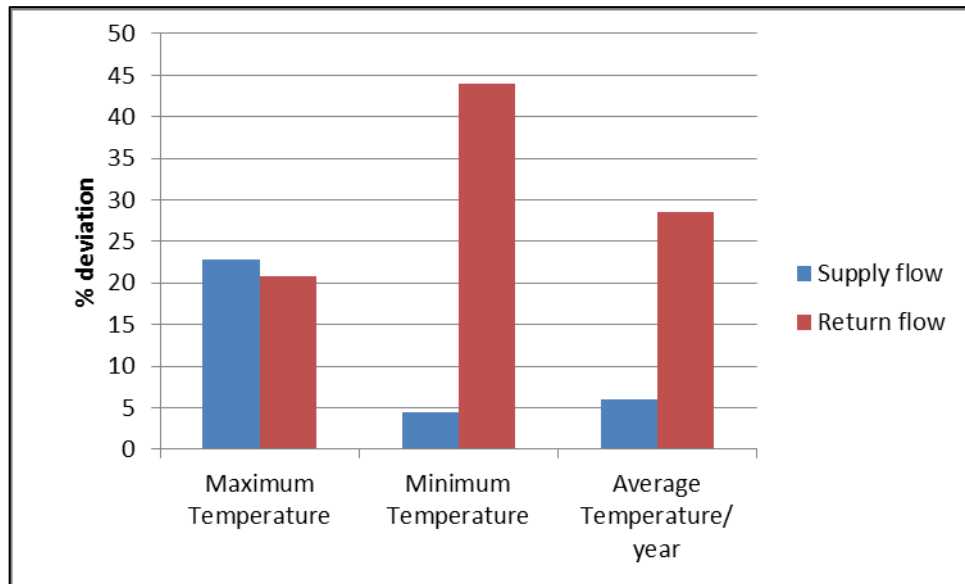


Figure 62: Percentage in deviation of different parameters in scenario 1 and scenario 3

From figure 62, it is observed that there is a deviation of approximately 21% for the maximum return flow temperatures between scenario's 1 and 3. For the minimum temperature in the return flow, there is a deviation of approximately 45%. The percentage deviation of maximum supply temperature is approximately 23%. At the same time, the minimum temperature deviation of the supply flow is approximately 4%. The difference in average temperatures for the return flow and supply flow have deviation's of 28% and 6% respectively. Although there is a deviation which can be seen from Figures 61 and 62 respectively. This occurs mainly due to the customised pipes and flow rate sources discussed in scenario 3.

5.1.3 Discussion of results in Summer and Winter

The scenario's 1 and 3 have been compared on a specific day in winter and summer. These are explained in detail in section 5.1.3.1 and 5.1.3.2.

5.1.3.1 Case study of a day in summer

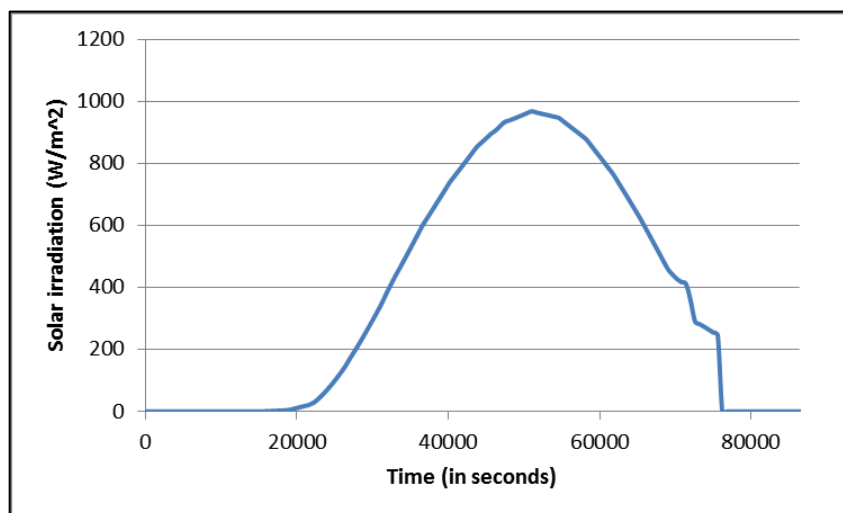


Figure 63: Solar irradiation data during a summer day

The figure 63 shows the solar irradiation during the most sunny day in summer used for simulating scenario 1 and 3. Based on the discussed case, a comparison of the temperature losses across the supply and return flow pipes in the district heating network are shown. In the figure's 64 and 65; the term's in the diagram are assigned a description which are shown in table 16.

Table 16: Description for the terms used in the simulation of the district heating network flow temperatures

Term	Description
FF_0	Supply temperature before passing through the district heating supply pipe
FF	Supply temperature exiting the district heating supply pipe
RF_0	Return flow temperature before entering the return flow pipe in the district heating network
RF	Return flow temperature exiting the return flow pipe

The figures 64 and 65 show the temperatures of the supply and return flow temperatures before and after losses through the pipe. This is done for both scenario's 1 and 3.

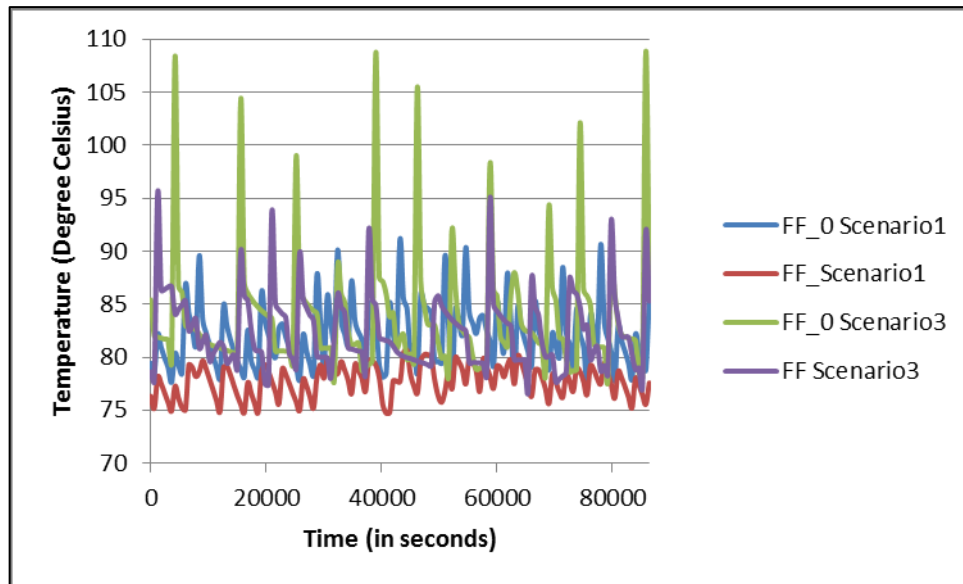


Figure 64: Temperatures of supply flow during a day in summer for scenario's 1 and 3

Figure 64 shows the supply flow temperatures for the district heating scenario's 1 and 3. Similarly figure 65 shows the return flow temperatures for the district heating scenario's 1 and 3. The two figure's 64 and 65 are shown for a sunny day in summer.

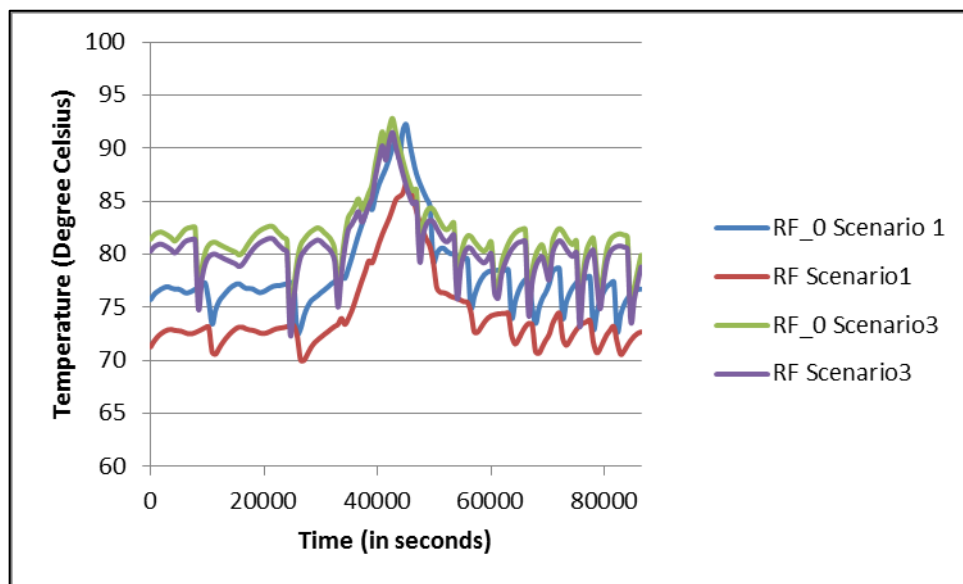


Figure 65: Temperatures of return flow during a day in summer for scenario's 1 and 3

As seen in figure 64, the supply inlet and exit temperatures of the flow from the central heating plant are almost constant within a range of 75°C to 85°C . There is a difference in the supply entry and exit temperatures across the piping in the supply side between scenario's 1 and 3. The reason is due to the definition of temperature losses across the pipe in the customised Simscape

pipe component. This is shown as attachment in the Appendix. There are sudden steep spikes in the supply flow entry and exit temperatures across the pipe in scenario 3. There is no occurrences of the sudden spikes in the supply temperature for the scenario 1 due to a constant capacity of the CARNOT pipe.

The figure 65 shows the return temperatures before and after exiting the return pipe in the district heating network for scenario's 1 and 3. As shown in Figure 63, during mid day there is high amount of total solar irradiation due to which the return flow temperature's increase across the pipe as compared to the early and later parts of the day. This gives a clear picture of the advantage of having decentralized solar collector's either on roof-tops or open land spaces. This means that the return temperatures of the district heating network increase by almost approximately 5-10°C with decentralized feed-in as in this case shown in figure 65 for scenario 1. For scenario 3, with customised Simscape pipe components, the loss in temperature across the return pipe less in the range of approximately 1-1.5°C during the duration of the day considered. This is explained with the low temperature losses of approximately 0.021°C/m for the return flow in scenario 3. This is seen in figure 66.

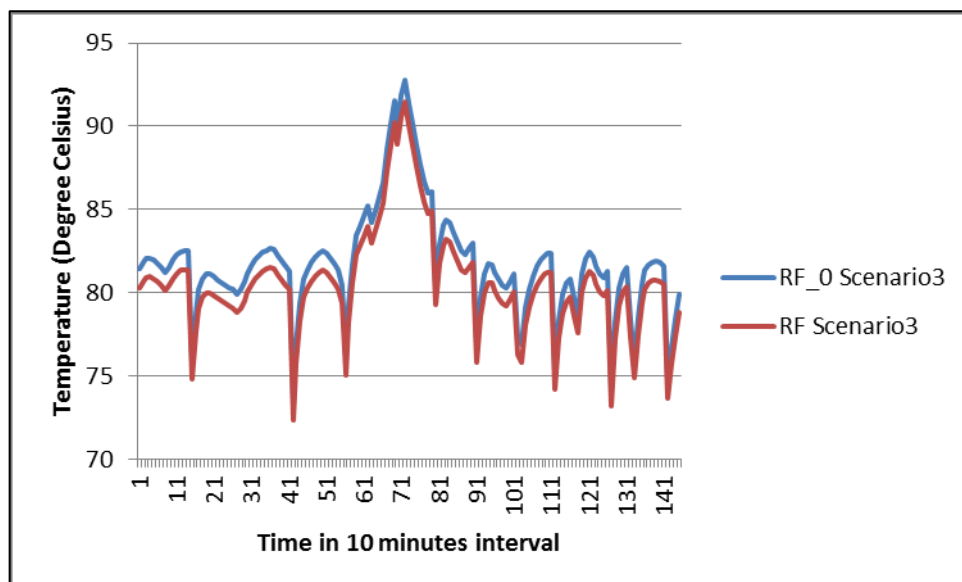


Figure 66: Return flow temperature before and after exiting return flow pipe on a summer day in scenario 3

There is a difference in the simulation results for scenario 1 and 3 return temperatures before and after leaving the return flow pipe. This is mainly due to

the customised Simscape components for the return pipe in the district heating network. This is seen in contrary to figure 66 in figure 67.

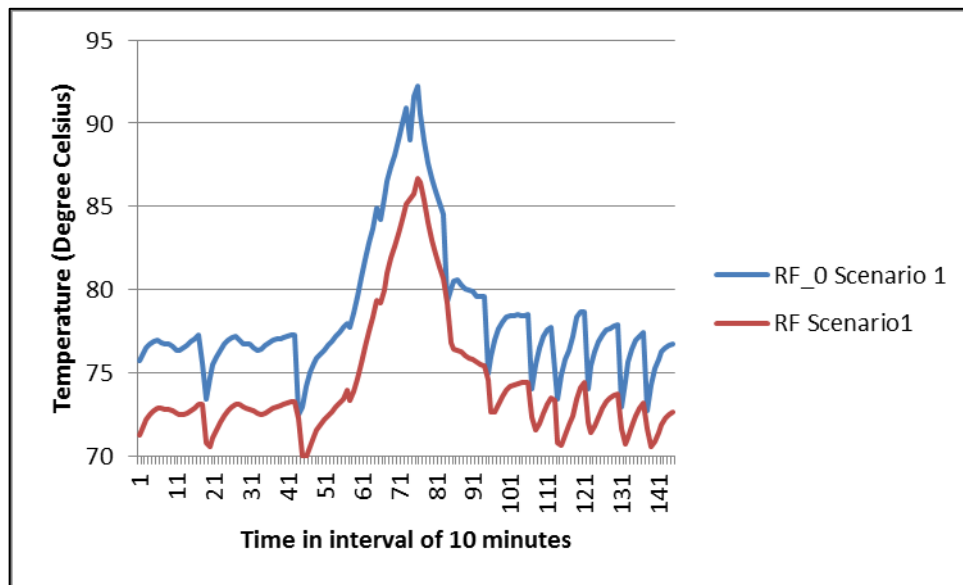


Figure 67: Return flow temperature before and after exiting return flow pipe on a summer day in scenario 1

It is observed from figure's 64 and 65 that the temperature losses across the district heating supply and return flow pipes are quite low in scenario 3 as compared to scenario 1. From figure 66, it is observed that there are certain areas where there is a rise in temperature for the return flow modelled in scenario 3. This is due to the non-consideration of a heat capacity in Simscape as compared to CARNOT Pipe components. For the scenario 1, the temperature losses per metre of the pipe as discussed in Chapter 4.1 is 0.086°C/m which is four times greater than in scenario 1. This explains the reason for the higher temperature losses in figure 67 as compared to figure 66.

5.1.3.2 Case study of a day in winter

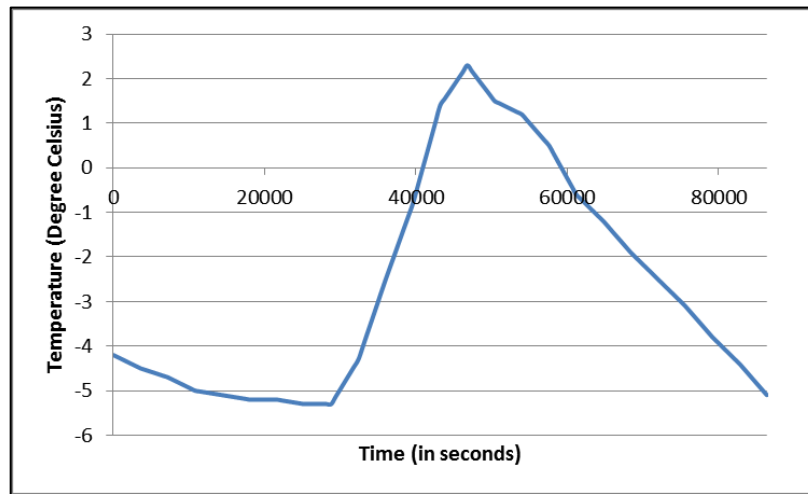


Figure 68: Temperature during a winter day for the case study

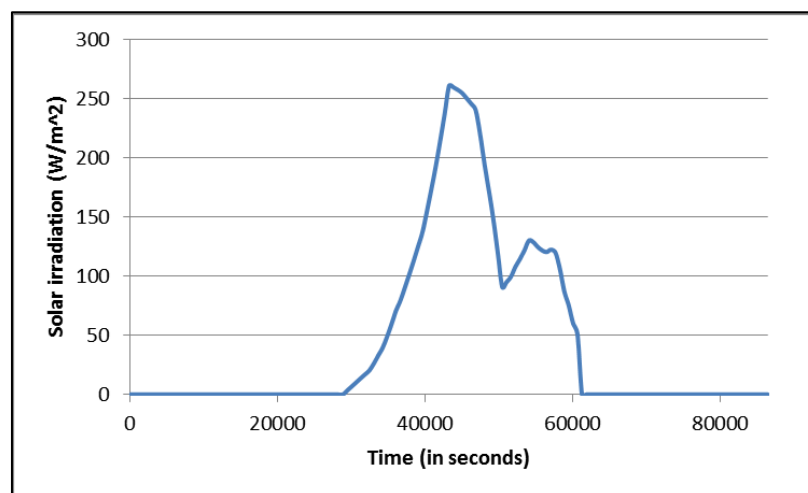


Figure 69: Solar irradiation during a cold winter day

Figure 69 shows the solar irradiation during a winter day used for simulating scenario's 1 and 3. The ambient temperature conditions are shown in figure 68. Based on the discussed case, a comparison of temperature losses across the supply and return flow pipes in the district heating network are shown in figures 70 and 71. The term's in the diagram are assigned a description which are shown in table 16 in the section 5.1.3.1.

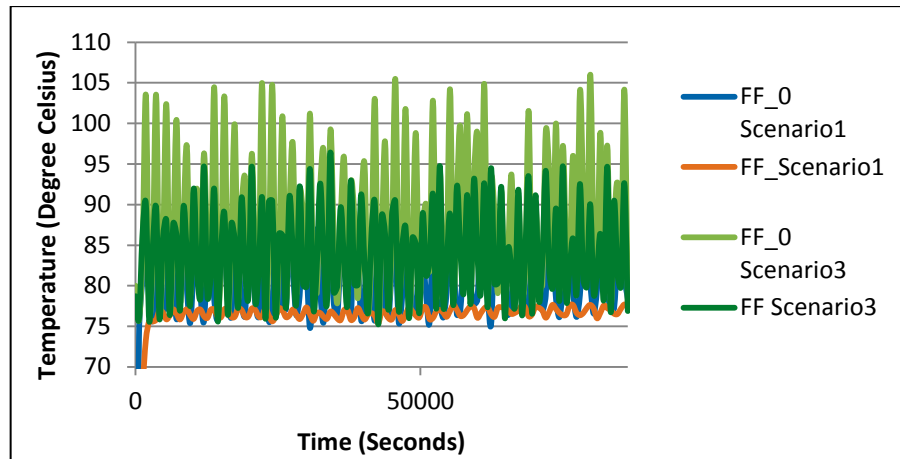


Figure 70: Temperature of supply flow during a day in winter for scenario's 1 and 3

As seen in figure 70, the supply temperatures from the central heating plant are almost constant within a certain range in both scenarios. Almost constant temperatures in FF_Scenario1 might come from the capacity of the CARNOT pipe. The capacity of the CARNOT pipe is set at 1000 J/m.K during the simulation which is the reason for the almost constant value. There is a difference between the entrance and the exit of the supply pipe due to the temperature losses to the ambient. The supply temperature's of the two scenario's are quite different from one another in scenario's 1 and 3. The reason is due to the definition of temperature losses across the pipe in the customised Simscape pipe component. This is shown as attachment in the Appendix.

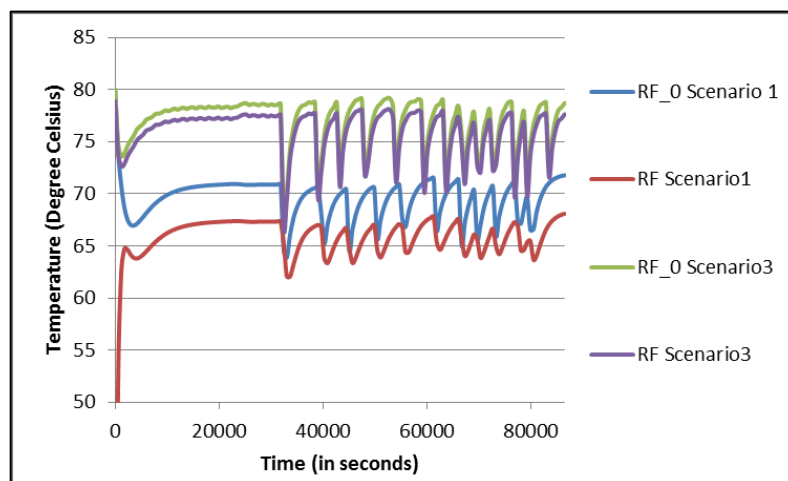


Figure 71: Temperature of return flow during a day in winter for scenario's 1 and 3

The figure 71 shows the return temperatures before and after exiting the return pipe in the district heating network for scenario's 1 and 3. There is a high

fluctuation of the return flow temperature before entering and after exiting the return pipe in scenario 3. This is due to the definition of the customised pipe component. There is no inclusion of constant capacity considered for the pipe component in scenario 3 which leads to fluctuations of temperatures. The temperature losses in the return flow pipe appear to be slightly lesser during a winter day as that of a summer day. The scenario 3 has low temperature losses during the winter day. There are abrupt changes in the temperature losses across the return pipe in scenario 3. This leads to high instability in the pipe return flow temperatures.

There is a marginal difference in the simulation results for scenario 1 and 3 return temperatures before and after leaving the return flow pipe. This is mainly due to the customised Simscape components for the return pipe in the district heating network.

A distinct characteristic is found in the return flow temperatures for scenario's 1 and 3. There is a more smooth nature of return flow temperature observed in scenario 1 as compared to scenario 3. This is due to the CARNOT pipe capacity = 1000 J/m.K which is set during the simulation. The return flow temperature of scenario 3 has a lot of sudden peaks and slopes during the winter day. This is due to the customised Simscape components used and due to the local solver settings for the Simscape configuration block. There is no definition of capacity as compared to CARNOT pipe component which leads to the sudden peaks and troughs in the flow temperatures. Inclusion of the capacity in the customised pipe components would smoothen these sudden peaks and troughs.

5.1.4 Conclusions

The Simscape customised pipe components have high fluctuations in temperature as discussed in the section 5.1 and its sub-chapters. The scenario 3 with customised pipe definition in Simscape appears to show lesser temperature losses during the various days of the year considered. The energy losses in the district heating network are slightly higher at around 2.57% for scenario 3 as compared to 2.03% for scenario 1. This subchapter 5.1 thus tested the unidirectional flow scenario's 1 and 3 for the temperature and energy loss comparisons.

5.2 Discussion of results between Scenario's 3 and 4

Scenario 3 is the system built with CARNOT block components for the prosumer's and the central heating plant. The district heating network pipes and flow rate source have been modelled using customised Simscape components. The solver configuration used for the Simscape components is the local solver type. The sample time set for this scenario is 10 in the Simscape configuration block. The scenario 4 is the system built with CARNOT block components same as scenario 3 but with a bi-directional behaviour as compared to a uni-directional behaviour in scenario 3.

As part of this section, the main purpose is to compare the results between the two scenario's 3 and 4 for uni-directional flow and bi-directional flow.

5.2.1 Energy losses in the district heating network

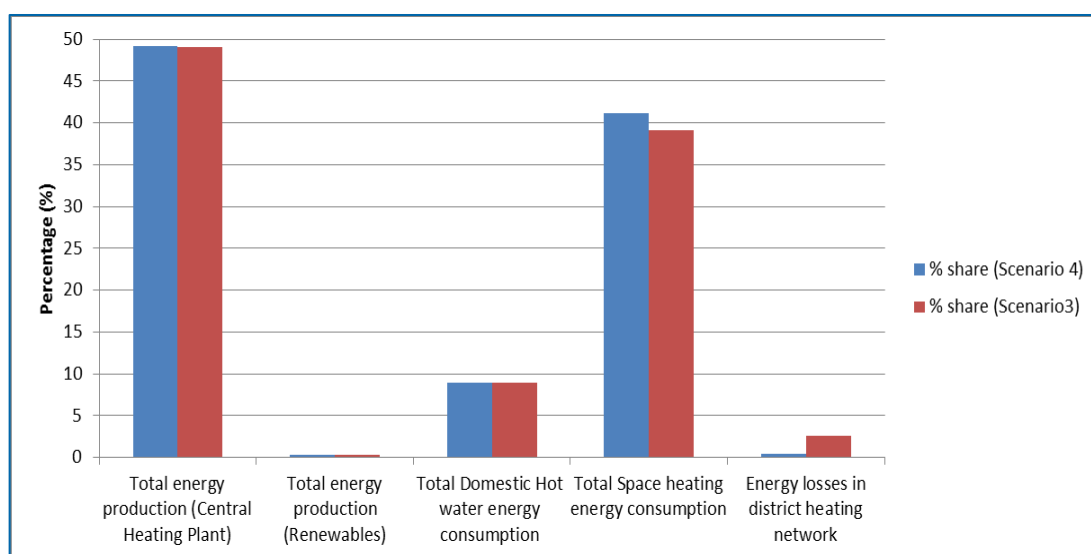


Figure 72: Comparison of energy production, consumption and losses between scenario's 3 and 4

Figure 72 shows the percentage share of production, consumption and losses between the two scenario's 3 and 4. It is clearly seen from this figure that the energy production, consumption (domestic hot water consumption and space heating) are the same for the two models. The only difference is the energy losses across the return and supply pipes in the district heating network which are quite different from one another. Scenario 4 with a bi-directional flow of the decentralized heat generators has a percentage of energy losses approximately equal to 0.4%. Scenario 3 with a uni-directional flow has a percentage of energy

losses equal to approximately 3%. This indicates that the bi-directional flow scenario has lower energy losses in the district heating network as compared to the uni-directional flow in scenario 3.

5.2.2 Supply and return flow temperatures in the district heating network

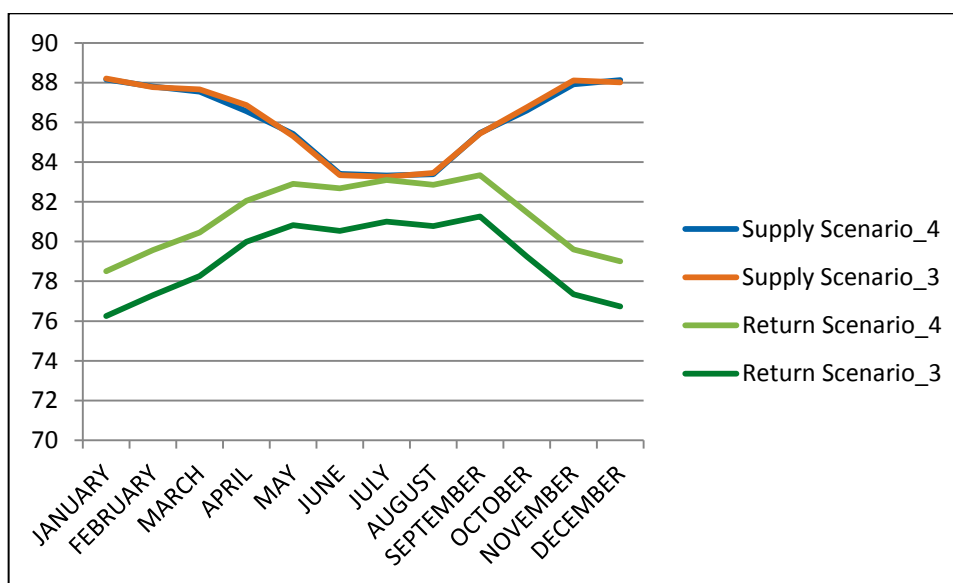


Figure 73: Supply and return temperatures for scenario's 3 and 4

Figure 73 depicts the average monthly supply and return temperatures in the district heating network for scenario's 3 and 4. It is clearly observed that the supply temperature's remain the same for scenario's 3 and 4. There is a decrease in temperature from the central heating plant due to the production of decentralized solar energy from the prosumer's end in both scenario's. The difference lies in the return temperatures. There is a constant offset of approximately 2°C seen for the return temperatures between scenario's 3 and 4. This is due to the bi-directional behaviour of the system in scenario 4. This is the reason between the month's June to August where the solar irradiation is quite higher and there is solar energy production at the prosumer's end, there is minimal temperature difference between the supply and return temperature. This means that most of the energy comes from the renewable energy production as compared to the central heating plant (fossil energy production).

5.2.3 Comparison of results during a day in summer

The scenario's 3 and 4 have been compared on a specific summer day. This is explained in detail in section 5.2.3.1.

5.2.3.1 Case study of a day in summer

The figure 63 in chapter 5.1.3.1 shows the solar irradiation during the most sunny day in summer used for simulating scenario's 3 and 4. Based on the discussed case, a comparison of the temperature losses across the supply and return flow pipes in the district heating network are shown. In the figure's 74 and 75; the term's in the diagram are assigned a description which are explained earlier within table 16 in chapter 5.1.3.1

The figures 74 and 75 show the temperatures of the supply and return flow temperatures before and after losses through the pipe. This is done for both scenario's 3 and 4.

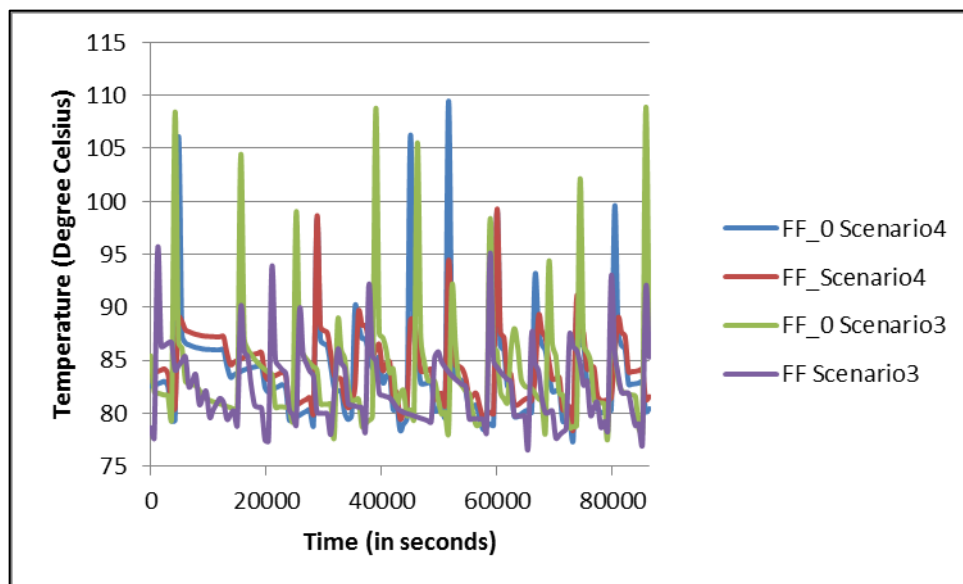


Figure 74: Temperature of supply flow during a day in summer for scenario's 3 and 4

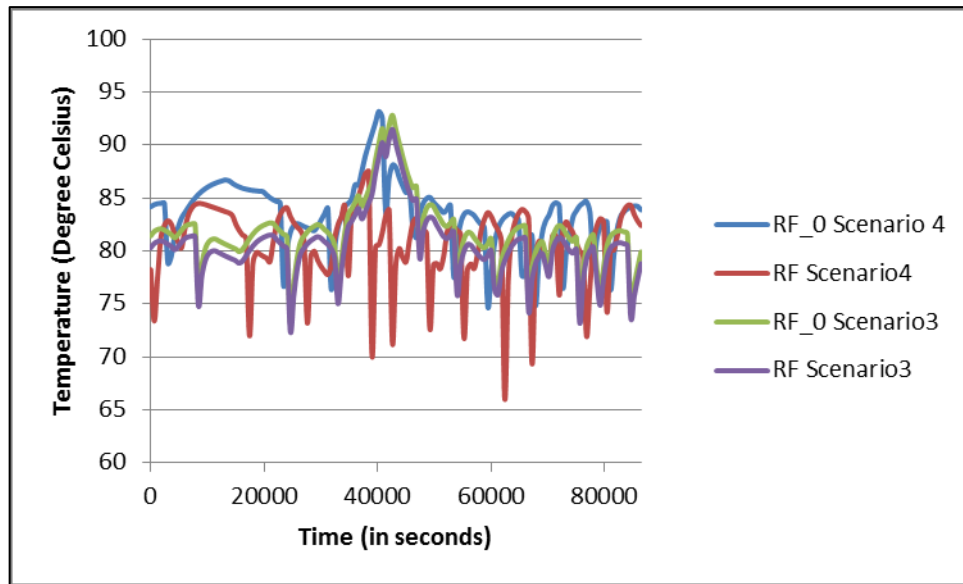


Figure 75: Temperature of return flow during a day in summer for scenario's 3 and 4

As seen in figure 74, the temperature of the supply flow in scenario 3 and 4 have almost the same behaviour. There are high peaks during the duration of the day of simulation which is primarily due to the customised pipe component definition in Simscape.

In figure 75, the return flow temperatures of the fluid in the district heating network are shown. The temperatures of the flow before and after exit in the return flow pipe appear to be reasonable. There appears a peak during the middle of the day for the return flow entry for scenario's 3 and 4. The scenario 3 exit temperature shows a slight loss in temperature across the length of the return pipe. Thereby, just showing a negative offset of approximately 1°C to the entrance temperature. For scenario 4, the exit temperature of the return pipe shows sudden dips in the temperature's during the middle of the day. This is due to the decentralized bi-directional flow of scenario 4. Scenario 3 return temperatures are much higher as compared to the return temperatures of the return flow in scenario 4. This is due to the uni-directional behaviour of scenario 3 as compared to scenario 4.

The mass flow rates of the system change when the temperature of the prosumer substation is greater than the temperature of the district heating

supply temperature. This negative flow creates the sudden dips in the temperature's of the return flow in scenario 4.

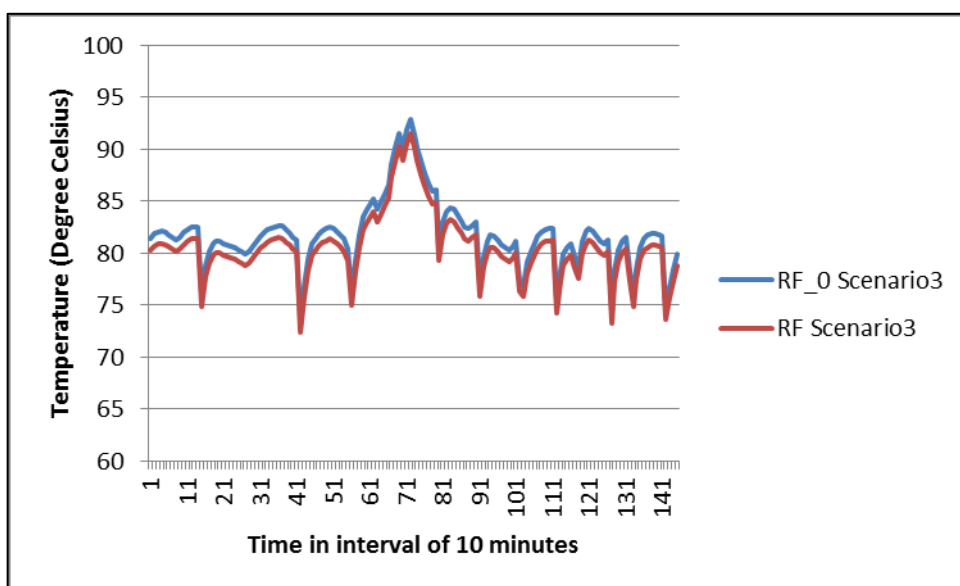


Figure 76: Return flow temperature before and after exiting return flow pipe on a summer day in scenario 3

There is a difference in the simulation results for scenario 3 and 4 return temperatures before and after leaving the return flow pipe. This is mainly due to the difference in flow behavior in the two scenario's.

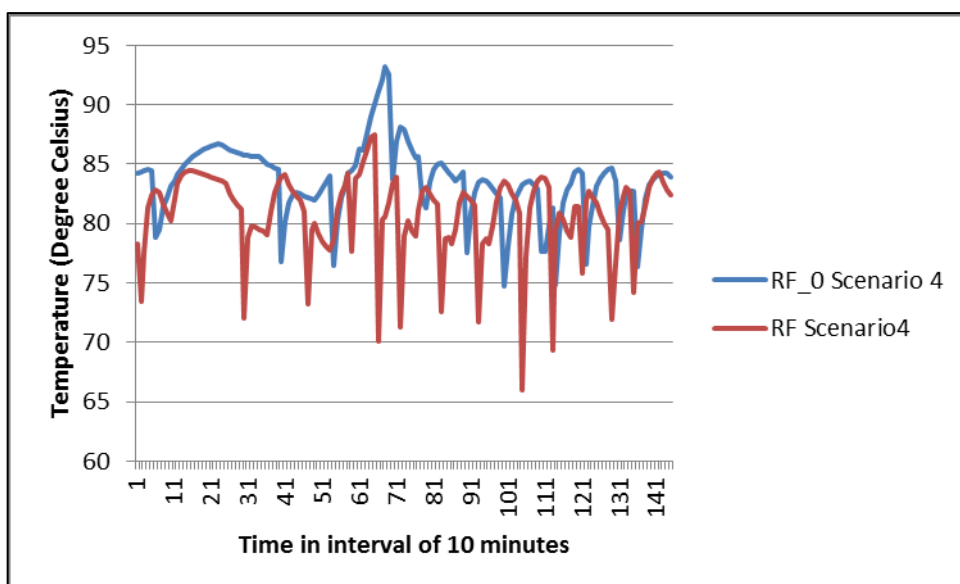


Figure 77: Return flow temperature before and after exiting return flow pipe on a summer day in scenario 4

5.2.4 Conclusions

The scenario's 3 and 4 have been compared as part of section 5.2. A specific day in summer is chosen, where temperature of the consumer storage is greater than the district heating supply temperature. In scenario 4 it is seen that the behaviour is bi-directional in nature where temperature losses are lesser as compared to the uni-directional flow behaviour in scenario 3. It is also observed that scenario 4 with a bi-directional flow has lesser energy losses in the district heating network as compared to scenario 3 with a uni-directional flow in the system.

It is also observed that the customised Simscape components show a lot of fluctuation in terms of sudden peaks and dips in temperatures during the year. This is due to not considering the capacity of the pipe as considered in the default CARNOT pipe component.

The subchapter 5.2 compares scenario's 3 and 4 between uni-directional flow of heat energy and a bi-directional flow of heat energy in the district heating network. In both of these scenario's, customised Simscape pipe components were used.

Chapter 6. Conclusions

The task is to model a district heating network with decentralized heat generators. This involved, if possible, to combine Simulink signals with physical signals in Simscape toolbox. To construct the model, the task consisted of the possibility to integrate the Simscape toolbox (Physical signal) in Simulink with CARNOT block components (Simulink signal). The main advantage envisaged of combining Simulink CARNOT block components with Simscape is the possibility of bi-directional flow.

As part of this thesis, I have attempted to explain step by step creation of this model. First, the customised Simscape components for the district heating network were modelled followed by modelling the component sub-systems at consumer and central heating plant in CARNOT. This process is explained in Chapter 3. The validation of these customised Simscape components against standard CARNOT components were made prior to creating the model.

The results show, that it is possible to make the model represent the district heating network.

In general, there are both pros and cons with physical modelling and specifically in Simscape. One of the advantages with physical modelling is the intuitive way the physical models are constructed by using components and physical relationships. It is also possible to have a bi-directional behavioural flow within the system in Simscape. That's the primary reason why integrating CARNOT with Simscape components stood to be one of the main challenges of this thesis.

The system with the customised Simscape components has a longer simulation time as compared to the system with only CARNOT block components. This is due to the change in signals at the interface between Simulink and Simscape.

The decentralized heat generators modelled in this system are solar flat plate collectors. The modelling of the decentralized heat generators have been made

using CARNOT block components. Based on real consumption data for space heating and domestic hot water consumption, the model was simulated for four separate scenarios and are discussed in chapters 4 and 5. As the secondary goals included investigation of temperature losses in the district heating network, these were achieved for the four scenarios simulated. The evaluation of the results for scenarios 1 and 3 have been discussed in detail in chapter 5. This includes comparisons between a pure Simulink signal model for scenario 1 and a combination of physical and Simulink signals model in scenario 3. The other comparison is between scenarios 3 and 4. This includes the comparison's between bi-directional flow in scenario 4 and a uni-directional flow behaviour in scenario 3. Both of these scenarios are modelled using customised Simscape components for the district heating network.

A very interesting concluding comment is the choice of the solver used for the scenarios. This plays a very crucial role for the simulation. Simscape components are compatible with the ode 23t variable or fixed solver type. In the solver configuration block for Simscape, the local solver settings work good with the CARNOT-Simulink combination. This is mainly used for moderately stiff problems, where the order of accuracy is low. CARNOT block components are compatible with the ode 23 solver type. Here the problem type is non-stiff. The order of accuracy is low in this case. The conclusions drawn forms a major part of this thesis on modelling a district heating network with customised Simscape and CARNOT block components.

Chapter 7. Scope for Future Work

Upon examining the results of scenario 3 (Chapter 4), it became apparent that improvements could be made. While the district heating model in scenario 3 outperforms the model in scenario 1, because of the functional combination of Simscape and CARNOT components which makes the system bi-directional in nature. In this case, the system in future could be tested with customised pump component (Attached in the Appendix) for decentralized heat generators as compared to the flow rate source. An opportunity for a research publication exists if a district heating model with decentralized heat generators modelled in Simscape could be used to simulate a realistic flow rate through the system at every interval of time.

As far as the scenarios in Chapter 4 are concerned, the system was having a constant mass flow rate in the network. This could be a main improvement that could be achieved in the future. This makes the system more realistic depending on the production and consumption of energy in the district heating network.

The modelled district heating system were for a central heating plant and a prosumer in the network. Research as part of this thesis to add more buildings in the system and to test the system for the same was attempted. Since, the district heating network was to be modelled in Simscape, modelling of the mixer or a diverter block for mixing or diversion of flow respectively in the network was not a part of this thesis. As a result, it was not possible to test the district heating network for more than two consumers. This could in future be considered for inclusion as a main point of further indepth research.

Modelling the system in Simscape is easier not only due to the bidirectional behaviour of flow but also due to the definition of the physical equations. This could also be a topic to be considered for future work in order to build the whole district heating network, which will include the consumer side and the decentralized heat generators with customised Simscape components.

Initially, testing the system with different heat generators was part of the plan for the thesis plan. The district heating model could be tested with various decentralized heat generators including heat pumps, geothermal energy etc. This would be an interesting factor to decide which of renewable energy would be energy efficient. The cost factors could also be further brought into the system in the future by adding a cost optimization model. Although, optimization of the model itself in terms of stability, effort and simulation time could be another scope for future work.

As promised customised Simscape thermohydraulic components has been shown in its current form to be capable of simulating district heating network with decentralized heat generators. While still there is considerable room for improvement, Simscape currently provides a significant contribution to the field of modelling bi-directional district heating networks with decentralized heat generators.

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APPENDIX

Domain and Component Definitions in Simscape

I. Domain

Domain: Thermohydraulics

```
1. domain thermohydraulics
    variables % across variables
        p = { 0 , 'Pa' }; % pressure
        t = { 0 , 'K' }; % temperature
    end
    variables(Balancing = true) % through variables
        qf = { 1 , 'm^3/s' }; % flow rate
    end
end
```

II. Components

Component: Thermohydraulic Reference

```
1.component thermohydraulic_reference
    nodes
        T = mysimscape.thermohydraulic.thermohydraulics; %
    T:top
    end
    variables(Access = protected)
        qf = { 0, 'm^3/s' }; % Flow rate
    end
    branches
        qf : T.qf -> *;
    end
    equations
        T.p == 0;
        T.t == {0, 'K'};
    end
end
```

Component: Flow Rate Sensor

```

2. component flowrate_sensor
outputs
    Q = { 0, 'm^3/s' }; % Q:right
end

nodes
    A = mysimscape.thermohydraulic.thermohydraulics; % A:left
    B = mysimscape.thermohydraulic.thermohydraulics; % B:right
end

variables(Access = protected)
    qf = { 1e-3 , 'm^3/s' }; % Flow rate
    p = { 0 , 'Pa' }; % Pressure differential
    t = { 0 , 'K' }; % Temperature differential
end

branches
    qf : A.qf -> B.qf;
end

equations
    t == A.t - B.t;
    t == 0;
    Q == qf;
    p == A.p - B.p;
    p == 0;
end
end

```

Component: Flow Rate Source

```

3. component flowrate_source
inputs
    S = { 0, 'm^3/s' }; % S:left
end

nodes
    T = mysimscape.thermohydraulic.thermohydraulics; % T:left
    P = mysimscape.thermohydraulic.thermohydraulics; % P:right

```

```

end

variables(Access = protected)
    qf = { 1e-3 , 'm^3/s'};      % Flow rate
    p  = { 0 ,   'Pa'   };      % Pressure drop
    t  = { 0 ,   'K'    };      % Temperature differential
end

branches
    qf : T.qf -> P.qf;
end

equations
    p == T.p - P.p;
    t == T.t - P.t;
    t == 0;
    if abs(S) >= {0.00001, 'm^3/s'}
        qf == S;
    else
        qf == {0.00001, 'm^3/s'};
    end
end
end

```

Component: Pipe

4. component pipe

```

nodes
A = mysimscape.thermohydraulic.thermohydraulics; % A:left
B = mysimscape.thermohydraulic.thermohydraulics; % B:right
end

variables qf = { 1 , 'm^3/s' }; % Flow rate
    p = { 0 ,   'Pa' };      % Pressure differential
    t = { 0 ,   'K' };      % temperature differential
end

parameters

```

```

% GENERAL
length = {10, 'm'};
innerdiameter = {0.022, 'm'};
% HYDRAULIC
roughnessfactor = {0.00015, 'm'};
rho = {1000, 'kg/m^3'};
viscosity = {0.000001, 'm^2/s'};
% THERMAL
T_amb = {293.15, 'K'};
Cp = {4190, 'J/(kg*K)'};
outerdiameter = {0.066, 'm'};
lambda = {0.04, 'W/(m*K)'};
end

branches
    qf : A.qf -> B.qf;
end

equations
    let
        % HYDRAULIC
Vm = qf/(pi*innerdiameter^2/4);
Re = abs(Vm*innerdiameter/viscosity);
f    =    0.25*(log10(roughnessfactor/3.7/innerdiameter    +
5.74/Re^0.9))^(-2); % Swamee-Jain equation for Re <2300 &&
Re >4000
        % THERMAL
T_avg = 0.5*(A.t + B.t);
    in
        % HYDRAULIC
p == f*length*rho*Vm^2/(2*innerdiameter);
p == A.p - B.p; % pressure differential

        % THERMAL
        t == B.t - A.t; % temperature differential
        if abs(qf) <= {0.000000000001, 'm^3/s'}
            B.t == T_amb;
        else

t == -(2*lambda*pi*(T_avg -

```

```
T_amb)*length*(log(outerdiameter/innerdiameter)*rho*qf*Cp) ^
(-1));
    end
end
end
end
```

Component: Pressure Sensor

```
5. component pressure_sensor
```

```
nodes
```

```
A = mysimscape.thermohydraulic.thermohydraulics; % A:left
B = mysimscape.thermohydraulic.thermohydraulics; % B:right
```

```
end
```

```
outputs
```

```
P = { 0, 'Pa' }; % P:right
```

```
end
```

```
variables(Access = private)
```

```
qf = { 0 , 'm^3/s' }; % Flow rate
p  = { 0 , 'Pa'   }; % Pressure differential
t  = { 0 , 'K'    }; % Temperature differential
```

```
end
```

```
branches
```

```
qf : A.qf -> B.qf;
```

```
end
```

```
equations
```

```
p == A.p - B.p;
P == p;
qf == 0;
t == A.t - B.t;
```

```
end
```

```
end
```

Component: Pump

6. component pump

```

inputs
    % Controller input
    S = { 0, '1' }; % S:left
end

nodes
    P = mysimscape.thermohydraulic.thermohydraulics; % P:left
    T = mysimscape.thermohydraulic.thermohydraulics; % T:right
end

variables
    qf = { 0 , 'm^3/s' }; % Flow rate
    p = { 0 , 'Pa' }; % Pressure differential
    t = { 0 , 'K' }; % temperature differential
end

parameters
    a = {-928.57, 'Pa/(m^6/s^2)'};
    b = {1614.3, 'Pa/(m^3/s)'};
    c = {37600, 'Pa'};
end

branches
    qf : P.qf -> T.qf;
end

equations
    if qf >= {0.0009, 'm^3/s'}
        p == (a*qf^2 + b*qf + c)*S;
    elseif qf < {0, 'm^3/s'}
        p == 0;
    else
        p == {41000, 'Pa'}*S;
    end
    p == T.p - P.p;

```

```

        t == T.t - P.t;
        t == 0;
    end
end

```

Component: Temperature Compensator

7. `component` temperature_compensator

`nodes`

```

A = mysimscape.thermohydraulic.thermohydraulics; % A:left
B = mysimscape.thermohydraulic.thermohydraulics; % B:right
end

```

`variables`(Access = protected)

```

    qf = { 1e-3 , 'm^3/s' }; % Flow rate
    p  = { 0 ,    'Pa' };    % Pressure differential
    t  = { 0 ,    'K' };     % Temperature differential
end

```

`branches`

```

    qf : A.qf -> B.qf;
end

```

`equations`

```

    t == A.t - B.t;
    p == A.p - B.p;
    p == 0;
end
end

```

Component: Temperature Sensor

8. `component` temperature_sensor

`nodes`

```

A = mysimscape.thermohydraulic.thermohydraulics; % A:left

```



```

    B = mysimscape.thermohydraulic.thermohydraulics; % B:right
end

outputs
    T = { 0, 'K' }; % T:right
end

variables(Access=private)
    qf = { 0 , 'm^3/s' }; % Flow rate
    p  = { 0 , 'Pa'   }; % Pressure differential
    t  = { 0 , 'K'    }; % Temperature differential
end

branches
    qf : A.qf -> B.qf;
end

equations
    t == B.t - A.t;
    T == t;
    qf == 0;
    p == A.p - B.p;
end
end

```

Component: Temperature Source

9. component temperature_source

```

inputs
    S = { 0, 'K' }; % S:left
end

nodes
    T = mysimscape.thermohydraulic.thermohydraulics; % T:left
    P = mysimscape.thermohydraulic.thermohydraulics;% P:right
end

```

```

variables(Access=private)
    qf = { 0 , 'm^3/s'};           % Flow rate
    p  = { 0 , 'Pa'   };           % Pressure differential
    t  = { 0 , 'K'    };           % temperature differential
end

branches
    qf : P.qf -> T.qf;
end

equations
    p == P.p - T.p;
    p == 0;
    t == P.t - T.t;
    P.t == S + {273.15, 'K'};
end
end

```