Research Centre on
ZERO EMISSION
NEIGHBOURHOODS
IN SMART CITIES

INTEGRATE DISTRICT HEATING MODULE

User guide and technical documentation

ZEN MEMO No. 34 – 2021

Hanne Kauko | SINTEF Energi

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Preface

Acknowledgements

This report has been written within the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The author gratefully acknowledge the support from the Research Council of Norway, the Norwegian University of Science and Technology (NTNU), SINTEF, the municipalities of Oslo, Bergen, Trondheim, Bodø, Bærum, Elverum and Steinkjer, Trøndelag county, Norwegian Directorate for Public Construction and Property Management, Norwegian Water Resources and Energy Directorate, Norwegian Building Authority, ByBo, Elverum Tomteselskap, TOBB, Snøhetta, Asplan Viak, Multiconsult, Sweco, Civitas, FutureBuilt, Hunton, Moelven, Norcem, Skanska, GK, Nord-Trøndelag Elektrisitetsverk - Energi, Smart Grid Services Cluster, Statkraft Varme, Energy Norway, Norsk Fjernvarme and AFRY.

The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities

The ZEN Research Centre develops solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contributes to a low carbon society.

Researchers, municipalities, industry and governmental organizations work together in the ZEN Research Centre in order to plan, develop and run neighbourhoods with zero greenhouse gas emissions. The ZEN Centre has nine pilot projects spread over all of Norway that encompass an area of more than 1 million m^2 and more than 30 000 inhabitants in total.

In order to achieve its high ambitions, the Centre will, together with its partners:

- Develop neighbourhood design and planning instruments while integrating science-based knowledge on greenhouse gas emissions;
- Create new business models, roles, and services that address the lack of flexibility towards markets and catalyze the development of innovations for a broader public use; This includes studies of political instruments and market design;
- Create cost effective and resource and energy efficient buildings by developing low carbon technologies and construction systems based on lifecycle design strategies;
- Develop technologies and solutions for the design and operation of energy flexible neighbourhoods;
- Develop a decision-support tool for optimizing local energy systems and their interaction with the larger system;
- Create and manage a series of neighbourhood-scale living labs, which will act as innovation hubs and a testing ground for the solutions developed in the ZEN Research Centre. The pilot projects are Furuset in Oslo, Fornebu in Bærum, Sluppen and Campus NTNU in Trondheim, an NRK-site in Steinkjer, Ydalir in Elverum, Campus Evenstad, NyBy Bodø, and Zero Village Bergen.

The ZEN Research Centre will last eight years (2017-2024), and the budget is approximately NOK 380 million, funded by the Research Council of Norway, the research partners NTNU and SINTEF, and the user partners from the private and public sector. The Norwegian University of Science and Technology (NTNU) is the host and leads the Centre together with SINTEF.

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Abstract

This memo describes the updated, 4th version of the district heating module for Integrate. The most important improvements with respect to the previous version are:

- The supply and return temperatures are not constant with hard-coded default values, but user-defined parameters that may be different for each season (segment)
- The power input for pumping of water in the piping network is defined as electricity input to the feed-in point and will therefore be a part of electricity supply into the system.
- Each pipe has a used-defined parameter for maximum heat demand, which enables a more accurate calculation of pressure loss and thus the required pumping work
- Dumping of heat is penalized
- Variable for total heat loss is included.

The main limitations of the module are:

- Temperature limitations/requirements at the load points or feed-in points are not considered; that is, the module considers only the required amount of energy required at the load point, or available from a source.
- The pressure losses over a load point are constant; that is, extra pressure losses occurring at customers closer to the heat source are not considered, which might lead into underestimation of the pumping power.
- Time delay for water flowing from a supply point to the load is not considered.

Contents

1. Introduction

Integrate is an optimization model developed for expansion planning in energy systems, where several alternative energy carriers and technologies are considered simultaneously. The model minimizes total energy system cost of meeting a predefined energy demand of e.g. electricity, heating, and cooling within a geographically confined area over a given planning horizon. The model considers investment, operating, and environmental costs over a planning horizon of several decades, and can represent the most relevant energy carriers and conversions between them.

District heating (DH) has an important role in future fossil free energy systems as it enables the utilization of energy sources that would otherwise be wasted to cover buildings' heating demands. Such energy sources may include industrial waste heat, urban waste heat sources such as data centres, or waste incineration. Utilization of DH for heating of buildings will alleviate the pressure on renewable power production and expansion of the electric grid and disengage grid capacity for other purposes, such as the transport sector. Integrate enables investment optimization of DH systems for confined areas, and comparison with alternative heat supply solutions with respect to investment and operational costs.

The DH module in Integrate includes several components: pipes, junction points, load points, and feed-in points for heat input. In this sense DH module deviates from the conventional formulation in Integrate of representing each component as one module. The reason for this is that the module contains correlations related to the heat transfer, heat loss and pressure drop, that involve several components, which thereby need to be seen under one module.

1.1 Improvements from the previous version

This version of the DH module includes several improvements with respect to the previous version, described in (Kvaslvik & Kauko, 2018):

- The supply and return temperatures are not constant with hard-coded default values, but user-defined parameters that may be different for each season (segment)
- The power input for pumping of water in the piping network is defined as electricity input to the feed-in point and will therefore be a part of electricity supply into the system.
- Each pipe has a used-defined parameter for maximum heat demand, which enables a more accurate calculation of pressure loss and thus the required pumping work
- Dumping of heat is penalized
- Variable for total heat loss is included

2 User guide

This chapter provides a practical description of the DH module and is meant for users of Integrate.

2.1 Description

The DH module includes, as mentioned above, production points for heat input, pipelines, junction points (network junctions), and load junctions. The load attached to a load point can be either a "heat load" or a "warm water load". The symbols for these components are shown in Figure 1. The remaining components shown in Figure 1 are not a part of the DH module but represent components that can be included as a part of a DH system. Heat storage (thermal storage tank) and seasonal storage are described in (Kauko, 2019). Note: The heat source -component represents an ambient heat source to a heat pump, and cannot be connected directly to a feed-in junction to supply heat to the DH network.

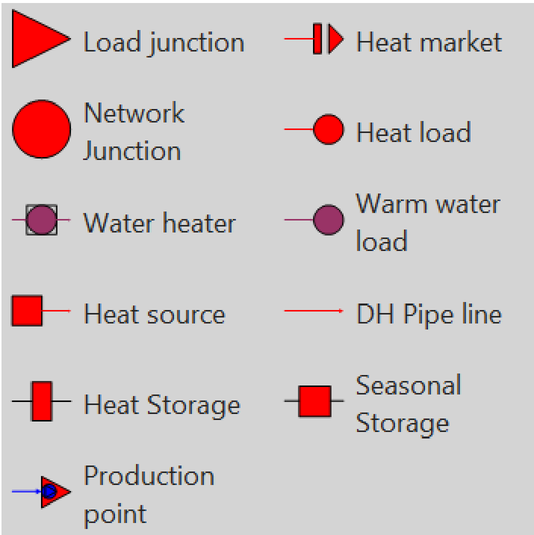

Figure 1. Symbols for the components in the DH module.

2.1.1 DH pipeline

The DH pipes can be connected between two junction points, between a junction point and a load point or a feed-in point, or between a feed-in point and a load point. A DH pipe has a certain direction, which determines the direction of positive mass flow and should be from the primary heat source to the load points. Inputs to the pipe are pipe length, maximum heat load delivered by the pipe and a user's heat loss factor. Note that the maximum heat load should be equal or higher than the heat load delivered by the pipe during the entire evaluated period. The user's heat loss factor is defined as a heat loss flow rate in W/K at a temperature difference of 40 °C between the supply temperature and the ambient, a value that can be obtained from DH pipe suppliers. The heat losses in are calculated according to

$$\dot{Q}_{loss} = K(T_{supply} - T_{amb})L \tag{1}$$

Where K is the heat loss factor in MW/(m*K), obtained from the user's heat loss factor by dividing it with $4*10^7$ to obtain it in the right units. See (Kvaslvik & Kauko, 2018) for more details.

The total heat losses vary typically from approximately 3 % of the total heat demand for a small network with high heat demand density, to up to 15 % for city-wide networks. It is advised for the user to check that the heat losses obtained with the selected heat loss factor are in a reasonable range with respect to the total heat demand, considering the total pipeline length in the network and the difference between the supply temperature and the ambient according to equation (1).

Output data from the DH pipe are the variables for positive and negative water flow ($DH\_Waterflow$ and $DH\_WaterflowN$), and pressure losses within the pipe ($PipePower$).

2.1.2 Load junction

The load junction, or a load point, needs to be connected to a heat load or a warm water load (symbols shown in Figure 1), that define the load over a 24-h period. The load junction has no input data. The outputs are heat deficit ($DH\_deficit\_load$) and pressure losses at the load ($LoadPower$).

2.1.3 Network junction

Network junction, or a junction point, connects two pipelines. It has no input or output data.

2.1.4 Feed-in junction

The feed-in junction, or production point, is the heat central supplying heat for the DH network. It needs to be connected to a heat source: a boiler, a heat pump, or a heat storage (seasonal or diurnal); as well as to an electricity source to cover the power demand for pumping. In addition, the pipes transporting heat to load points are connected to the production points. Feed-in junction has no input data. The outputs are heat deficit ($DH\_deficit\_prod$) and dumped heat (DH_dump_load).

2.2 Assumptions and limitations

The following main limitations have been identified:

- Temperature limitations/requirements at the load points or feed-in points are not considered; that is, the module considers only the required amount of energy required at the load point, or available from a source. Thus, the user needs to make sure that the selected heat sources are able to supply heat at the required temperature level in the network; and that the customers are able to satisfy their heat demands at this temperature level.
- The pressure losses over a load point are constant; that is, extra pressure losses occurring at customers closer to the heat source are not considered (see section 0), which might lead into underestimation of the pumping power.
- Time delay for water flowing from a supply point to the load is not considered.

3 Technical documentation

The amount of energy supplied at a given point in a DH system is affected both by the water temperature and the water flow, as given by the expression:

$$\dot{Q} = \dot{V} c_p (T_{supply} - T_{return}) \quad (2)$$

where $\dot{Q}$ is the heat flow; $\dot{V}$ the volume flow of water; c_p is the specific heat capacity of water; and T_{supply} and T_{return} are the supply and return temperatures water, respectively. This gives a non-linear optimization problem for the operation of the network. In a linear representation of a DH system, either the flow or the temperature thus needs to be a parameter. We have chosen to set the supply and return temperatures as parameters, while the water flow is a variable, which allows the calculation of pressure drop and thereby pump work input to the model. The supply and return temperature are however defined in the "Edit segments" -dialogue in Integrate and can thus have different values in different seasons.

To preserve the linearity of the formulation, and yet to be able to calculate the heat losses occurring in pipes, a variable named $\dot{Q}_{less}$ is introduced, defined as *the heat removed from the water after it left the heat central*. That is,

$$\dot{Q}_{less} = \dot{V} c_p (T_{supply} - T_{water}) \quad (3)$$

Where T_{supply} is the supply temperature at the production site, and T_{water} is the water temperature at the node in question. Notice that T_{water} is never calculated in the model – equation (3) is rather given as an exact definition for $\dot{Q}_{less}$.

This section describes the sets, parameters and variables, as well as the objective function and constraints in the DH module

3.1 Sets

Table 1 presents the sets included in the DH module.

Table 1. Sets in the DH module

Symbol	Explanation	**Unit**
$DH\_Junction\_points_j$	Network junctions	-
$DH\_Load\_points_l$	Load junctions	-
$DH\_Production\_points_p$	Feed-in junctions	-
$DH\_el\_inputs_{ep}$	Electricity input for pumping at production points	-
$DH\_heat\_inputs_{hp}$	Heat input	
$set\ DH\_Points$	All points within the DH network	-
$DH\_Exchange\_points$	Points where the DH network can be connected to other modules in Integrate (Network nodes)	-
$DH\_Directions_d := \{"DH\_OUT","DH\_BACK"\}$	Set of directions for water in pipes. "DH_OUT" is supply from the heat central to the load, "DH_BACK" is the return flow.	-
$DH\_ends_e := \{"DH\_THIS","DH\_FAR"\}$	Set of the different ends for DH pipes. "DH_THIS" is the end listed first in the ordered pair defining a pipeline, "DH_FAR" is the end listed last. The end closest to the production point should be listed first.	-
$DH\_Pipe\_lines_{i,j}$	DH pipelines. Defined from the direction of positive flow: from feed-in point to the load point.	

3.2 Parameters

Table 2 shows the parameters included in the DH module. Note that the unit MW corresponds to MWh/h. The index *t* refers to time.

Table 2. Parameters in the DH module.

Symbol	Explanation	Unit
Heat supply		
$DH\_Water\_heating\_factor$	Specific heat capacity of water (c_p in eq. (1)), set to 4.2.	MW/[(m^3/s)*K]
$Users\_heat\_loss\_factor_{i,j}$	User-defined heat loss factor in pipes at a $DT = T_{supply} - T_{amb} = 40K$	W/m
$DH\_heat\_loss\_factor_{i,j}$	*Users_heat_loss_factor* converted to right units for calculating heat loss. Default: *Users_heat_loss_factor*[i,j]/40000000	MW/(m*K)
$DH\_max\_demand_{i,j}$	Parameter for max demand delivered by a pipe.	MW
$DH\_prod\_deficit\_penalty_p$	Penalty for not delivering the required demand at the production points.	-
$DH\_prod\_dump\_penalty_p$	Penalty for dumping of heat.	-
$DH\_load\_deficit\_penalty_l$	Penalty for not delivering the required demand at loads.	-
Temperature		
T_supply	Supply temperature	°C
T_return	Return temperature	°C
T_min_supply	Minimum supply temperature to limit heat losses. Default: $T\_supply - 3$	°C
Pressure		
$dp\_DH\_load\ \ default$ 0.07	Guaranteed pressure drop across a load	MPa
$Rvalue\ default$ 150	Allowed max pressure drop in pipes	Pa/m
$DH\_Pipe\_Length_{i,j}$	Length of a pipe	m
Water flow		
$max\_water\_flow_{i,j}$	Max water flow in each pipe, calculated from the max demand as $DH\_max\_demand/(DH\_Water\_heating\_factor * (T\_min\_supply - T\_return))$;	m^3/s
Pumping power		
$pumpEff_p$	Pumping efficiency	
$nProductionPoints$	Number of production points	

3.3 Variables

Table 3 presents the variables included in the DH module.

Table 3. Variables in the DH module.

Symbol	Explanation	Unit
Heat supply		
$Qless_{(i,j),e,d,t}$	Determines the heat demand in each pipe in the network	MW
$Qloss\_tot_t$	Total heat loss in all pipes	MW
$DH\_demand_{p,t}$	The total heat demand at each production point	MW
$DH\_dump\_load_{p,t}$	Dumped heat load at production points	MW
$DH\_deficit\_prod_{p,t}$	Deficit heat at production points	MW
$DH\_deficit\_load_{l,t}$	Deficit heat at load points	MW
Water flow		
$DH\_Waterflow_{(i,j),t}$	Water flow in each pipe	m^3/s
$DH\_WaterflowN_{(i,j),t}$	Water flow in opposite direction	m^3/s
Pumping power		
$PipePower_{(i,j),t}$	Pumping power due to pressure loss in pipes	MW
$LoadPower_{l,t}$	Pumping power due to pressure loss at loads	MW
$DH\_pump\_work_{p,t}$	Power demand for pumping	MW

3.4 Objective function

The objective of the DH module is to satisfy the demand with minimum heat deficit. In addition to heat deficit at production points and loads, dumping of heat at the feed-in point is penalized:

$$\begin{aligned} objective&[\mathrm{DISTRICT\_HEATING}] \\ &= \sum_{p,t} DH\_dump\_load_{p,t} \cdot DH\_prod\_dump\_penalty_{p,t} + \sum_{p,t} DH\_deficit\_prod_{p,t} \\ &\cdot DH\_prod\_deficit\_penalty_{p,t} + \sum_{l,t} DH\_deficit\_load_{l,t} \cdot DH\_load\_deficit\_penalty_{l,t} \end{aligned} \tag{4}$$

The deficit and dump penalties are user-defined parameters.

3.5 Constraints

3.5.1 Energy flows in and out from the system

The heat demand needs to be covered by *supply_flow* and/or *net2net_flow* to heat input points *hp* at production points *p*:

$$\begin{aligned} DH\_demand\_(p,t) & \\ &= \sum_{(s,hp)\in Supply2net} Connection\_loss\_factor_{s,hp} \cdot supply\_flow_{s,hp,t} \\ &+ \sum_{(s,hp)\in Net2net} Connection\_loss\_factor_{s,hp} \cdot net2net\_flow_{s,hp,t} - DH\_dump\_load_{p,t} \\ &+ DH\_deficit\_prod_{p,t} \end{aligned} \tag{5}$$

The power demand for pumping connected to electricity input points *ep* at the feed-in points *p* needs to be covered by *supply_flow* and/or *net2net_flow:*

$$DH\_pump\_work_{p,t} = \sum_{(s,ep)\in Supply2net} Connection\_loss\_factor_{s,ep} \cdot supply\_flow_{s,ep,t} + \sum_{(s,ep)\in Net2net} Connection\_loss\_factor_{s,ep} \cdot net2net\_flow_{s,ep,t} \tag{6}$$

3.5.2 Internal constraints

Heat flow

The required heat supply is defined by the variable $Qless$ in the return line:

$$DH\_demand_{p,t} = \sum_{(hp,i)\in DH\_Pipe\_lines} Qless_{(hp,i),\,\mathrm{DH\_BACK,\,DH\_THIS,\,t}} \tag{7}$$

The following constraint makes sure that the water flow is sufficient to cover the load, including heat losses and possible heat deficit:

$\forall (l,j) \in Net2load$:

$$Qless_{(i,l),\,\mathrm{DH\_OUT,\,DH\_FAR},t} + load\_flow_{(l,j),t} + DH\_deficit\_load_{l,t} \leq DH\_Water\_heating\_factor_{(i,l)} \cdot (T\_supply - T\_return) \cdot DH\_Waterflow_{(i,l),t} \tag{8}$$

At the load points, the heat demand ($load\_flow$) is added to the variable $Qless$:

$$\sum_{(i,l)\,\in\, DH\_Pipe\_lines} Qless_{(i,l),\,\mathrm{DH\_OUT,\,DH\_FAR},t} + \sum_{(l,j)\,\in\, Net2load} load\_flow_{(l,j),t} = \sum_{(i,l)\,\in\, DH\_Pipe\_lines} Qless_{(i,l),\,\mathrm{DH\_BACK,\,DH\_FAR},t} \tag{9}$$

At junction points, the energy balance needs to be satisfied; that is, the sum of energy flowing in and out of the node needs to be zero. For the sake of clarity, this is defined separately for supply and return lines:

$$\sum_{(i,j)\,\in\, DH\_Pipe\_lines} Qless_{(i,j),\,\mathrm{DH\_OUT,\,DH\_FAR},t} = \sum_{(j,k)\,\in\, DH\_Pipe\_lines} Qless_{(j,k),\,\mathrm{DH\_OUT,\,DH\_THIS},t}$$
$$\sum_{(i,j)\,\in\, DH\_Pipe\_lines} Qless_{(i,j),\,\mathrm{DH\_BACK,\,DH\_FAR},t} = \sum_{(j,k)\,\in\, DH\_Pipe\_lines} Qless_{(j,k),\,\mathrm{DH\_BACK,\,DH\_THIS},t} \tag{10}$$

Heat losses

The following constraint calculates the heat loss for a pipe in the supply line, and adds the loss to the far end of the pipe:

$$Qless_{(i,j),\,\mathrm{DH\_OUT,\,DH\_FAR},t} = Qless_{(i,j),\,\mathrm{DH\_OUT,\,DH\_THIS},t} + DH\_Pipe\_Length_{i,j} * (T\_supply - Outdoor\_temp) * DH\_Heat\_loss\_factor_{i,j} \tag{11}$$

The following constraint is set to make sure that the temperature drop due to heat loss is within the allowed range:

$$Qless_{(i,j),\,\mathrm{DH\_OUT},\,\mathrm{DH\_FAR},t} \leq DH\_Water\_heating\_factor \cdot (T\_supply - T\_min\_supply) \cdot DH\_Waterflow_{(i,l),t} \tag{12}$$

It is also required that heat loss in the supply line is positive:

$$Qless_{(i,j),\,\mathrm{DH\_OUT},\,\mathrm{DH\_THIS},t} \geq 0; \tag{13}$$

Without this requirement, the lost heat may be heat input to the system.

Heat losses in the return line are generally very small, and in any case much smaller than the losses in the supply pipes (Dalla Rosa, 2011). Losses in the return pipe can even be negative in twin pipes, as heat leaks from the supply to the return line. It was thus decided that the model should not have heat losses in the return lines:

$$Qless_{(i,j),\,\mathrm{DH\_BACK},\,\mathrm{DH\_FAR},t} = Qless_{(i,j),\,\mathrm{DH\_BACK},\,\mathrm{DH\_THIS},t} \tag{14}$$

.

In addition, the following constraint is included to make sure that the heat loss does not become negative:

$$Qless_{(i,j),\,\mathrm{DH\_BACK},\,\mathrm{DH\_FAR},t} \geq 0 \tag{15}$$

Mass flow

At junction points, mass balance needs to be satisfied; that is, the sum of water flowing in and out of a junction point needs to be zero:

$$\sum_{(i,j)\in DH\_Pipe\_lines} \left[DH\_Water\_flow_{(i,j),t} + DH\_Water\_flowN_{(i,j),t}\right] = \sum_{(j,k)\in DH\_Pipe\_lines} \left[DH\_Water\_flow_{(j,k),t} + DH\_Water\_flowN_{(j,k),t}\right] \tag{16}$$

This covers both positive and negative water flow (DH_Water_flowN). Negative water flow (opposite flow direction) might occur if there are several feed-in points or prosumers (consumers and producers of heat) in the network, or if a circular network is considered. Water flow in negative direction must however not occur at load points or production points:

$$DH\_Water\_flow_{(i,l),t} = 0 \tag{17}$$

$$DH\_Water\_flow_{(hp,i),t} = 0 \tag{18}$$

For sources, the following constraint is set to ensure that waterflow is zero if there is no heat flow from the source; and that heat flow is nonzero if waterflow is nonzero:

$$DH\_Water\_flow_{(hp,i),t} \leq Qless_{(hp,i),\,\mathrm{DH\_BACK},\,\mathrm{DH\_THIS},t} / DH\_Water\_heating\_factor \tag{19}$$

Pumping power

Pressure drop is what causes the demand for pumping water. The power demand P of a pump is given by:

$$P = \frac{dp\dot{V}}{\eta} \tag{20}$$

Where dp is the pressure drop, and η the pumping efficiency. The calculation is divided into two parts: the required pumping power due to pressure drop in pipes, and the required power due to pressure drop at loads. DH pumps are generally placed at the heat source, and the required pressure lift is then determined by the total pressure drop from the heat supplier to the load furthest away multiplied by two (for water flow out and back), plus the pressure drop at the loads. Figure 2 illustrates the problem.

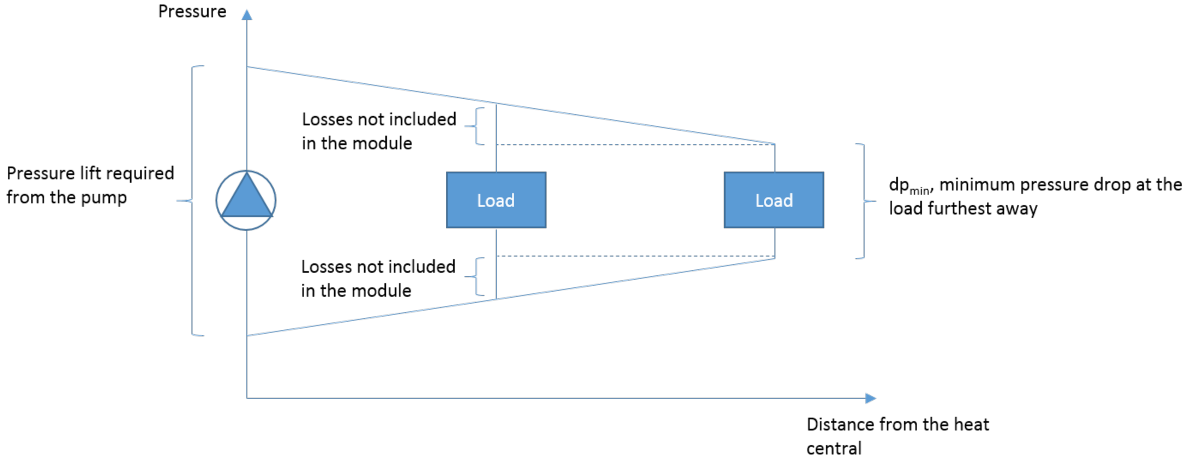

Figure 2. Illustration of the pressure drop as a function of distance from a heat central, and the pressure losses occurring at loads.

The pressure drop in pipes depends on the pipe and the fluid properties, but can be expressed in a simple form using the maximum allowed pressure drop per metre at a given maximum water flow, $\dot{V}_{max}$, known as the R-value:

$$dp = RL\left(\frac{\dot{V}}{\dot{V}_{max}}\right)^2 \tag{20}$$

The pumping power due to pressure losses in pipes thus becomes

$$P = \frac{dp\dot{V}}{\eta} = \frac{RL}{\eta}\left(\frac{\dot{V}}{\dot{V}_{max}}\right)^2 \dot{V} \propto \dot{V}^3 \tag{21}$$

To be able to represent this nonlinear dependency in Integrate, a piecewise linear approximation using non-dimensional variables is applied, shown in Figure 3. The details of this approach can be found in (Kvaslvik & Kauko, 2018). In Integrate, the pumping power due to pressure losses in pipes is calculated as follows:

$$
\begin{aligned}
PipePower_{(i,j),t} \le{}& (DH\_Waterflow_{(i,j),t} - DH\_WaterflowN_{(i,j),t})/max\_water\_flow_{i,j} * Rvalue * 10^{-6} \\
& * DH\_Pipe\_Length_{i,j} * max\_water\_flow_{i,j}; \\
PipePower_{(i,j),t} \ge{}& 0.1075 \cdot (DH\_Waterflow_{(i,j),t} - DH\_WaterflowN_{(i,j),t})/max\_water\_flow_{i,j} * Rvalue * 10^{-6} \\
& * DH\_Pipe\_Length_{i,j} * max\_water\_flow_{i,j}; \\
PipePower_{(i,j),t} \ge{}& (-0.3749 + 1.0044 * (DH\_Waterflow_{(i,j),t} - DH\_WaterflowN_{(i,j),t})/max\_water\_flow_{i,j} * Rvalue \\
& * 10^{-6} * DH\_Pipe\_Length_{i,j} * max\_water\_flow_{i,j}; \\
PipePower_{(i,j),t} \ge{}& (-1.3317 + 2.3095 \cdot (DH\_Waterflow_{(i,j),t} - DH\_WaterflowN_{(i,j),t})/max\_water\_flow_{i,j} * Rvalue \\
& * 10^{-6} * DH\_Pipe\_Length_{i,j} * max\_water\_flow_{i,j};
\end{aligned}
\tag{22}
$$

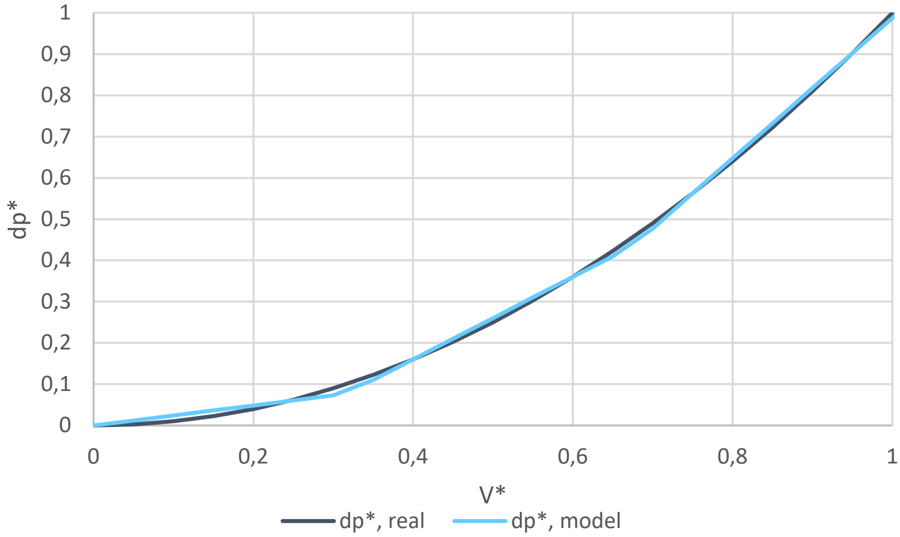

Figure 3. Dimensionless pressure drop "dp*, real" as a function of volume flow, and piecewise linear dimensionless pressure drop "dp*, model"

At the loads, the volume flow depends on the heat load as shown by Equation (7). The pressure drop *dp* is known for the load furthest away – this is the minimum pressure drop the DH provider is obliged to deliver for their customers, set to 0.7 bar in Trondheim. For loads closer to the heat supplier however, the pressure drop will be larger than this as shown in Figure 2. The local pressure drop at loads closer to the supplier is dependent on the local pressure, which is a variable. For the sake of simplicity, this extra pressure drop was hence omitted in the present model. The pumping power due to pressure drop at each load point *l* is then calculated as

$$LoadPower_{l,t} = dp\_DH\_Load \cdot Qless_{(i,l),\,\mathrm{DH\_BACK,\,DH\_FAR},t} / (T\_supply - T\_return) / DH\_Water\_heating\_factor \tag{23}$$

The power consumption at the production points *p* is then calculated as

$$DH\_el\_consumption_{p,t} \cdot nProductionPoints \cdot pumpEff = \sum_{(i,j)\,\in\,DH\_Pipe\_lines} 2 * PipePower_{(i,j),t} + \sum_{l\,\in\,DH\_Load\_points} LoadPower_{l,t} \tag{24}$$

4 Verification

Figure 4 shows a test network applied in verification of the DH module, consisting of:

- Two heat sources, an electric and a bio source, and the associated boilers (conversion units) and, feed-in points to the DH network
- Two junction points
- Two load points and the associated heat loads; one constant and one variable
- In total five pipes with a length of 1000 m each connecting the feed-in points, junction points and load points

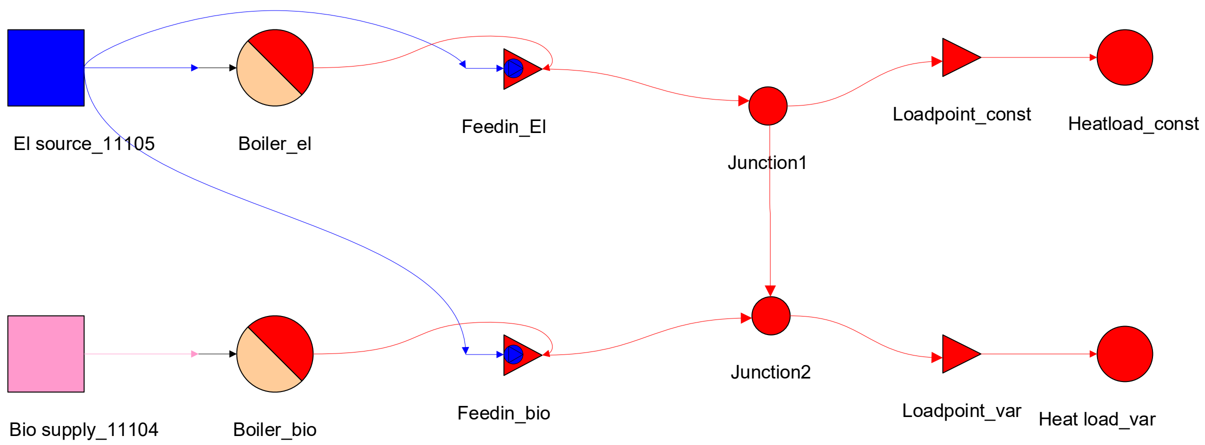

Figure 4. Test network applied in verification of the DH module.

Figure 5 presents results from an operational optimization with the test network, showing the total heat demand (including heat losses), heat supply from the el and the bio boiler, as well as the costs for the two sources. The bio source is the preferred source most of the time, apart from the period 2-4 when the electricity prices are equal to or lower than the price for bio.

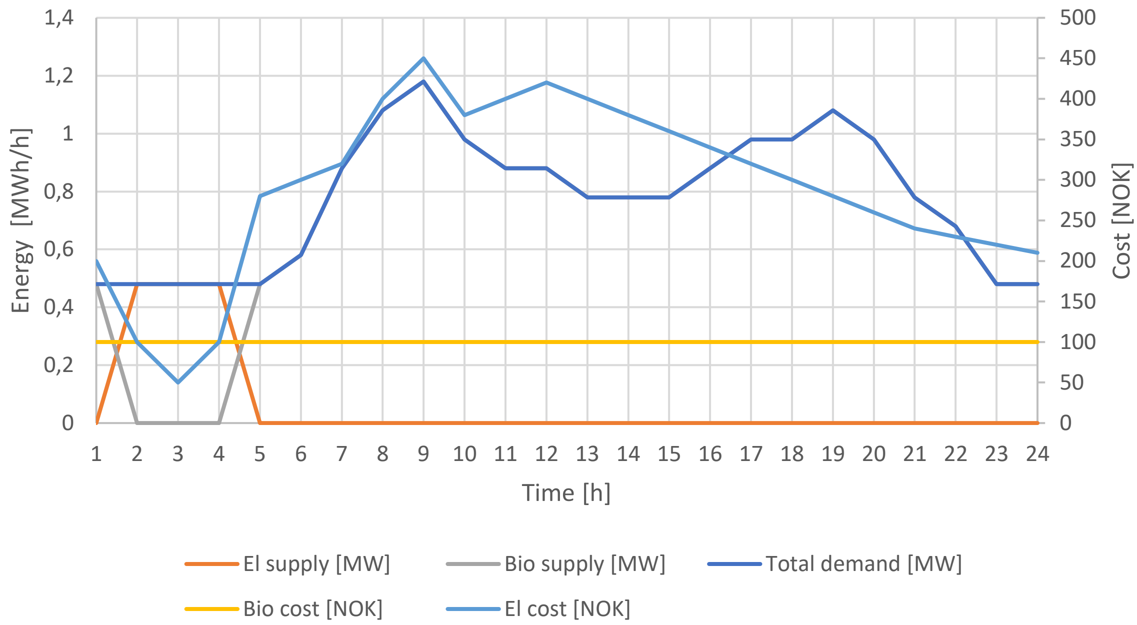

Figure 5. Results from a 24-h operational optimization with the test network.

Since the bio boiler is the preferred source for most of the time, and the pipeline joining Junction point 1 and 2 is defined in this order, negative flow occurs in this pipeline, but the model handles this well. Figure 6 shows the mass flow in the pipe connecting junction points 1 and 2. When the flow is positive, the electric boiler covers most of both the heat loads, and when it is negative, the bio boiler covers the loads.

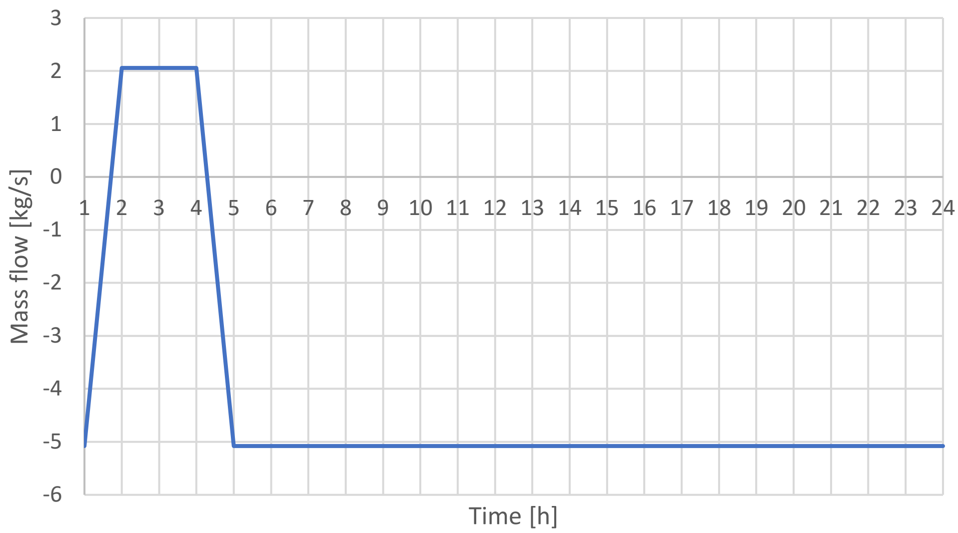

Figure 6. Mass flow in the pipe connecting junction points 1 and 2.

Figure 7. Heat losses and pump work. shows additionally the heat losses and pump work in the network. The heat losses are constant, since the outdoor and supply temperatures are constant, set to 1 °C and 65 °C, respectively. The pump work is minimal with respect to the heat losses; and both heat losses and pump work are minimal with respect to the total heat demand shown in Figure 5. It may be argued that including pumping power in the model is not so relevant; however, it may become of importance when

comparing DH network with different supply temperature levels. Low-temperature DH networks are usually characterized by low temperature difference between supply and return line, resulting in high mass flow rate and consequently high pumping power.

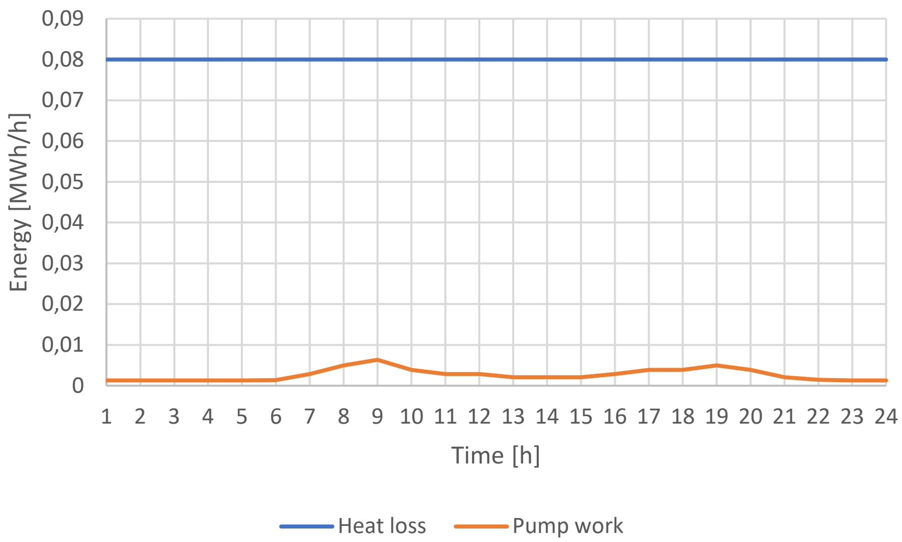

Figure 7. Heat losses and pump work.

5 Conclusions

An updated version, considered as the 4th version of the district heating module, has been implemented. The most important improvements with respect to the previous version are including pumping power as electricity input in the feed-in points, and having supply and return temperature as user-defined, season-dependent parameters. Based on the initial tests, the module works as intended.

The main limitation of the module is that temperature limitations/requirements at the load points or feed-in points are not considered. This functionality could be implemented in the future if it is considered to be relevant.

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