D6.11 – Pre-design support online tool

Fifth generation, low temperature, high exergy district heating and cooling networks
FLEXYNETS

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1 Introduction

1.1 Principle scheme of the FLEXYNETS system

An Excel tool was developed to carry out preliminary feasibility studies on the implementation of the FLEXYNETS concept in different scenarios.

The Excel tool was developed based on a 2-pipe network configuration, whose principle scheme is shown in Figure 1. Individual reversible heat pumps (*HP* in Figure 1) installed at the consumers' location draw flow from the network supply pipe, regardless of whether they are in heating or cooling mode. The advantage of this connection is that the pressure difference between supply and return pipe leads the flow across the heat pumps. Another option could have been that the heat pumps reverse the flow direction (i.e. drawing water from the return pipe) in cooling mode. So, the performance of the heat pumps is enhanced and mixing of flows at different temperatures is avoided, but a pump is needed to overcome the pressure difference between supply and return pipe. In case of small heat pumps and/or small amounts of condensing heat, the investment and operation costs for additional pumps is unlikely to be recovered. On the other hand, the possible availability of large amounts of waste heat from industrial plants or large chillers (*Waste heat* in Figure 1) may justify the cost of a pump reversing the flow.

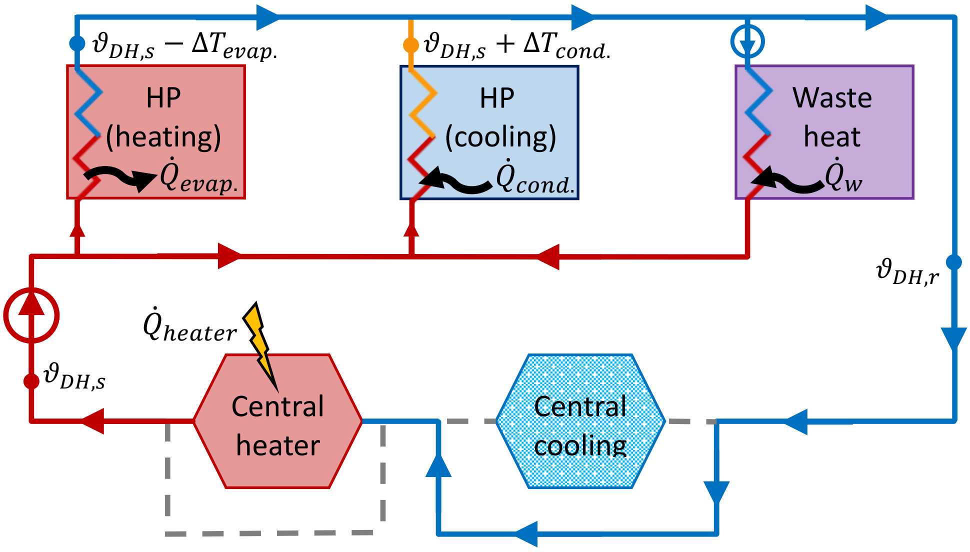

Figure 1: Principle scheme of a FLEXYNETS system.

When the heat drawn at the evaporator of the heat pumps in heating mode ($\dot{Q}_{evap.}$) is larger than that injected by the condenser of the heat pumps in cooling mode ($\dot{Q}_{cond.}$), the network return temperature ($\vartheta_{DH,r}$) is lower than the supply temperature ($\vartheta_{DH,s}$). The heater at the central plant supplies energy ($\dot{Q}_{heater}$) to compensate for this temperature difference.

The energy that the heater at the central plant must provide to the network can be reduced, if waste heat ($\dot{Q}_{w}$) is available. In the Excel tool, two conditions must be satisfied for the waste heat to be supplied to the network. First, the waste heat temperature should be higher than or equal to the network supply temperature. Waste heat temperatures higher than the network supply temperature

are tempered down to the network supply temperature, so that all consumers are supplied with the same temperature (apart from thermal losses), no matter their proximity to the waste heat source. Secondly, the amount of waste heat injected into the network cannot be larger than the net heat load of the network, i.e. the amount that the central heater would have to supply, if waste heat were not available. Excess amounts of waste heat are assumed to be dissipated to the environment, unless the option of including a seasonal pit thermal energy storage (PTES) in connection to a specific waste heat source is selected (see Section 3.1 and 3.7).
Conversely, if the heat injected into the network by the condensers of the heat pumps in cooling mode is larger than that drawn by the evaporators of the heat pumps in heating mode, the return temperature is higher than the supply temperature and the central cooling system turns on. The central cooling system consists of a water/water central chiller and a cooling tower. If the ambient temperature is sufficiently low compared to the network supply temperature, heat is removed from the network through the cooling tower only. If the ambient temperature is too high, heat is removed from the network at the evaporator of the central chiller, boosted to a sufficiently high temperature and so rejected to the environment through the cooling tower.

Although the primary scope of the developed Excel tool is to assess the feasibility of a FLEXYNETS system, the tool can also be used to investigate the implementation of a conventional district heating (DH) system, which represents a convenient benchmark. However, while conventional DH supplies only heating, a FLEXYNETS system is meant to cover simultaneously both heating and cooling demands. To make the comparison between the two systems fair, the cooling demand should somehow be covered also in case of conventional DH. This is done assuming that the cooling demand is covered by individual vapor-compression cooling machines.

A description of this pre-design tool is given in Section 3, where each subsection describes the function a worksheet of the Excel file, to better guide the user in the use of the tool. Although the authors tried to be as clear and linear as possible, the different worksheets have a strong interdependence between one other, so that a strictly logical and causal presentation of the worksheets was not possible. Hence, the reader will often find references to previous and following sections, and he/she should have a synoptic approach to the manual to achieve a better understanding of the tool.

2 Quick Start Guide

The user should always define the main boundary conditions in the "Inputs" worksheet, filling or editing the values in the orange cells. Yellow cells are also user-defined inputs, but in this case the inserted value must be selected among the limited number of options appearing in the dropdown menu. Although most of the user-inputs are specified in the "Inputs" worksheet, other parameters can be still edited by the user in most of the other worksheets (see Figure 2). However, the customizable parameters in these worksheets have default values, which are used, unless the user overwrites them. The user recognizes the cells which can be edited by the user through their orange (or yellow) background color, as explained above.

Beside a user-input cell, one of the icons shown in table below will often appear. The user should take care of verifying the inputted value, if a yellow or red icon appears.

Symbol	Description
	The inserted value is realistic, and it respects other boundary conditions/parameters specified in the tool
	The inserted value seems unrealistic but still respects other boundary conditions/parameters specified in the tool. If the user is confident in the specified value, she/he can continue with the definition of the inputs.
	The inserted value does not respect other boundary conditions/parameters specified in the tool. If the tool still returns an output, this is to be considered invalid. The user should identify the problem and solve it, before continuing with the definition of the inputs.

INSERT DATA IN THE ORANGE CELLS, CHOOSE FROM DROPDOWN MENUS IN YELLOW CELLS			
Geographical location	North Europe		
Type of district	Unpaved area/New district		
Type of DH network	Flexynets		
Composition of urban area	Land area [km^2]	Heat demand [GWh/km^2/a]	Plot ratio [-]
Low density residential	0.3	18.0	0.22
High density residential	0.7	50.0	0.80
Public	0.0	20.0	0.30
Light industry	0.0	18.0	0.60
Heavy industry	0.0	16.0	0.10
Other (areas with no/negligible demand)	0.0	2.0	0.06
Total land area [km^2]	1.00		
Yearly heat demand [GWh]	40.4		
Number of loads [-]	500		
DH supply temperature [°C]	To be inputted in 'HourlyAna		
DH return temperature [°C]	Not defined for Flexynets		
Type of pipes	SERIES 1		
Yearly cooling demand [GWh/a]	12.0		
Waste heat	Amount available [GWh/a]	Temperature [°C]	
source 1 (s1)	20	90	
source 2 (s2)	5	50	
source 3 (s3)	5	25	
Waste heat source connected to PTES	1		
Base-load heater technology (aux 1)	Gas boiler		
Back-up heater technology (aux 2)	Electric boiler		
Cost of waste heat [EUR/MWh]	5.00		
Interest rate [%/a]	2.5%		

Figure 2: Appearance of the "Inputs" worksheet in the Excel tool.

In the worksheet "PTES" the user can run a VBA macro to see the effect that a water pit storage connected to one of the waste heat sources has on the performance of the system. To run the macro, the user must have specified from the appropriate dropdown menu in the "Inputs" worksheet the waste heat source to which she/he wants the PTES to be connected to. If this is the case, she/he just needs to

press the grey button “PTES sizing”. The main parameters in the scenario without and with PTES are summarized in two tables. The variation in overall cost and overall environmental emissions are also shown. Based on the results, the user can choose in the appropriate dropdown menu whether to implement the PTES or not. The choice affects how the main results are shown in the “Summary” worksheet.
The main outputs of the Excel tool, such as installed capacities, yearly energy balances and costs, are found in the worksheet “Summary”. Two sets of values always appear in the worksheet, one referring to Conventional DH and the other to a FLENYNETS system. It should be noted that only the set referring to the selected type of network in the “Inputs” worksheet is relevant. The values of the other set (which is automatically greyed out) have no meaning and should be disregarded.

3 Description of the pre-design Excel tool

3.1 “Inputs” worksheet

In the worksheet “Inputs” the user needs to insert some general information on the case-study to be investigated. Although the user can modify many more parameters also in the other worksheets to customize the model for specific boundary conditions, the worksheet “Inputs” comprehends the minimum amount of inputs needed by the Excel tool.
The required inputs include type of network (Conventional DH or FLEXYNETS), geographical location (Northern, Central or Southern Europe), number of consumers connected to the network, extension and composition of the urban area. The composition of the urban area is defined according to the simplified categorization of settlement typologies presented in (Jensen, 2016; section 2.2.3), which distinguishes between low/high density residential areas, public building areas, light/heavy industry areas and other zones (such as parks, churches, etc.), characterized by a very low heating/cooling demand. Based on (Jensen, 2016), default values of yearly heat demand per unit land area and of plot ratio are suggested for each typology. As the specific heat demands from (Jensen, 2016) refer to Denmark, these are proposed as default values for Northern Europe. For Central and Southern Europe these values were corrected through Eq. 1, based on the *European heating index* (Frederiksen, 2013; Figure 4.5) and the ratio between the yearly space heating (SH) demand and the yearly heat demand. The default values of yearly heat demand for each geographical location are automatically inserted in the worksheet, when the user selects a location. The calculation of the demands according to Eq. 1 is performed in the worksheet “Dropdowns”, but it is mentioned in this section for better contextualization. The yearly heat demand includes both SH and domestic hot water (DHW).

$$\frac{Q_{dem.,h,i}}{A_L} = \frac{Q_{dem.,h,ref}}{A_L} \cdot \frac{f_{SH,ref}}{f_{SH,i}} \cdot \frac{EHI_i}{EHI_{ref}} \qquad \text{(Eq. 1)}$$

where $Q_{dem.,h}$ is the yearly heating demand referring to the area A_L, [MWh];
A_L is the land area, [m^2];
f_{SH} is the ratio between the yearly SH demand and the yearly heat demand, [-];
EHI is the European heating index (see Section 3.3) [-];
Subscript i refers to the specific geographical area considered, while subscript ref refers to the geographical area taken as reference, in this case Northern Europe.

The assumed value of the above-mentioned parameters is found in Table 1 and Table 2 in Appendix A. These default values can be edited by the user, if he has data more representative of the case study under investigation.
Based on the above-mentioned inputs and assumptions, the yearly heat demand is calculated. On the other hand, the yearly cooling demand needs to be specified by the user, as the market penetration of cooling is much more case-dependent than that of heating and hence difficult to estimate *a priori*.
It should be noted that, while in case of a conventional DH network the cumulated heat demand of the consumer is equal to the network heat load (when network heat losses are considered too), in a FLEXYNETS network this consideration cannot be made. This is caused by the presence of the heat pumps as well as by the simultaneous supply of heating and cooling from the same network. The electricity input to the heat pumps in heating mode entails that the heat demand of a building is higher than the heat that the heat pump must draw from the network, with the difference corresponding to the electricity consumed by the heat pump. Hence, the lower the COP of the heat pump, the less heat the heat pump draws from the network. On the other hand, the electricity input to the heat pumps in cooling mode entails that the cooling demand of a building is lower than the corresponding cooling demand that the network will have to dissipate, this being the sum of the building cooling demand and the electricity consumed by the heat pump. Hence, the lower the COP of the heat pump, the more heat the network receives from the heat pump and the higher the network cooling demand.

Regarding the distribution network, constant supply and return temperatures need to be specified in case of conventional DH. In case of a FLEXYNETS system only the network supply temperature is a user's input, while the return temperature results from the mixing of the outlet flows from the evaporators of the heat pumps in heating mode and from the condensers of the heat pumps in cooling mode.
Additionally, the insulation class of the network pipes (SERIES 1, 2 or 3 (Logstor, 2017)) and the type of soil to be excavated (paved or unpaved) need to be specified.

Up to three waste heat sources can be entered by specifying the amount and the temperature of the waste heat available, as well as the price at which the waste heat is purchased by the manager of the network. The waste heat temperature to be inserted is not strictly the temperature at which waste heat is available, but more properly the temperature to which a flow at the DH return temperature can be heated up. For example, if an amount of waste heat is available at 80 °C, but a minimum temperature difference of 5 K is expected to occur across the heat exchanger between the waste heat source and the DH network, a temperature of 75 °C should be inserted instead of 80 °C. Additionally, the waste heat source is treated as a constant temperature heat source (such as a condenser), so that the entire amount of waste heat available can be transferred to the DH network, regardless of its return temperature.
Regarding the price of waste heat, this should include the investment cost of the components and the labor cost needed to establish the connection between the waste heat facility and the distribution network, such as pumps, heat exchangers, transmission pipes, etc. A detailed method for estimating the component of the waste heat price that reflects the investment cost for the transmission pipes is described in another deliverable of the FLEXYNETS project (Sveinbjörnsson, 2018; Chapter 4). Additionally, the user can specify whether a seasonal PTES is present and to which of the three waste heat sources this is connected to (see Section 3.7).

Finally, the type of the base load heater and of the back-up heater are to be specified, selecting them from a list of different technologies (see Section 3.5).

3.2 "Load Profiles" worksheet

As seen in Section 3.1, the Excel tool receives the yearly demand for heating and cooling as input. However, the load profiles on an hourly basis throughout the year are necessary to carry out a prefeasibility study. For example, to size appropriately components such as distribution network, central heating/cooling plant, substations and heat pumps, the peak loads are needed. Additionally, in presence of non-linear relations, such as that between pumped flow rate and pumping power, time-averaged quantities are likely to lead to inaccurate results, so instantaneous values should be used.

In the Excel tool the hourly heating and cooling demand (see Eq. 2) are estimated based on the yearly demands and on the load profiles, which can be found (and edited, if needed) in the "Load profile" worksheet. The heating/cooling demand in each hour of the year, $Q(t)$, is calculated combining the yearly load profile YLP (defined on a monthly basis) with a daily load profile DLP (one for each season and defined on an hourly basis). A consequence of this simplified approach is that the hourly demands of all the days within the same month are identical.

$$\begin{cases} Q(m) = Q_{yearly} \cdot YLP(m) \\ Q(t) = Q(m) \cdot DLP(s,t) \end{cases} \quad \text{(Eq. 2)}$$

where $Q(m)$ is the heating/cooling demand in the month m, [MWh];
Q_{yearly} is the yearly heating/cooling demand, [MWh];
$YLP(m)$ is the fraction of yearly demand which is required in the month m, [-];
$Q(t)$ is the hourly demand at the time t of any day of the month m, [MWh];
$DLP(s,m)$ is the fraction of daily demand which is required in the hour t, [-]. The daily load profile DLP is function of the season s, to which the month m belongs.

The profiles of the available waste heat sources are defined in the same way.

The highest hourly heating and cooling demands throughout the year can be assumed as peak demands and used to size the system components. Because this approach implicitly makes an average over each month of the single daily load profiles (all days in a month are assumed being identical in terms of hourly load), the actual peak heating demand which may characterize only few days of the year is evened out by the lower demand in the other days of the same month. Hence, if the user is aware that the expected peak heat demand is higher than that resulting from the load profiles, she/he can correct the latter with a safety factor (≥1).

The user can define both yearly and daily load profiles. Otherwise, default profiles, function of the geographical location, are used. These were obtained from the data presented in (Frederiksen, 2013; chapter 5.5 and 5.7) referring to the DH and district cooling network in Helsingborg (Sweden), and extrapolating them to the other geographical locations based on the different weather conditions. Examples of default daily load profiles are shown in Figure 3, while the default yearly load profiles for heating and cooling demand assumed by the Excel tool are shown in Appendix A (Figure 4 and Figure 5).

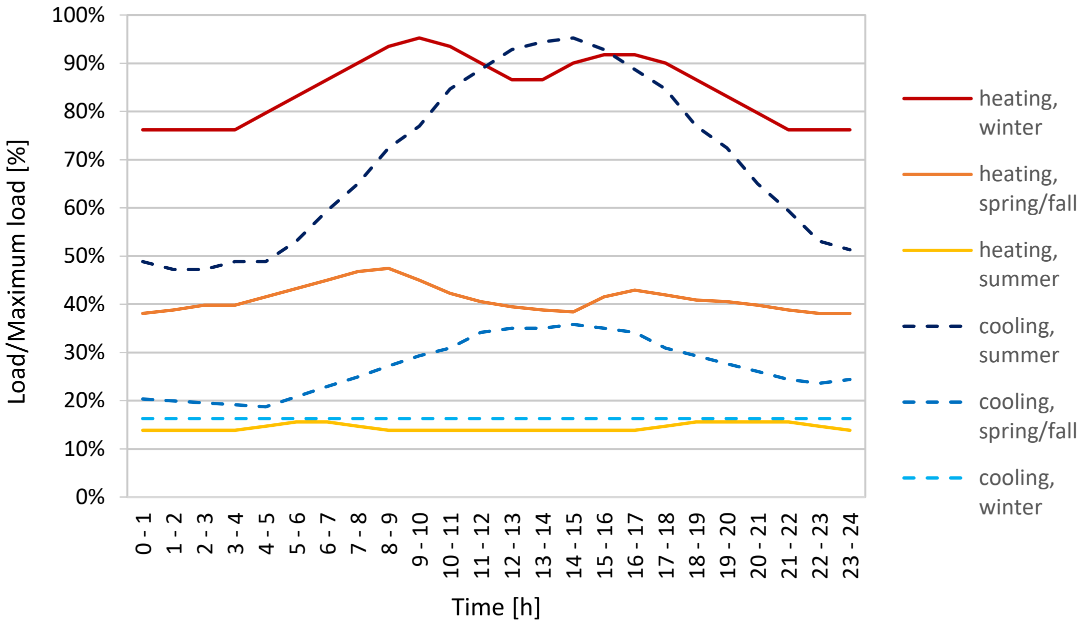

Figure 3: Example of daily load profiles for heating and cooling demands in different seasons. The different months of the year are assigned to one of three available seasons (winter, spring/fall and summer), which affect the shape of the daily load profile. The criterion by which the months are assigned to a specific season is shown in Table 3 in Appendix A.

3.3 "Dropdowns" worksheet

This worksheet contains the boundary conditions which are function of the geographical location, as well as the temperature levels of the heating and cooling loads.

3.3.1 Ambient temperatures and related parameters

Among the first conditions there are weather parameters, such as average of the highest and of the lowest ambient temperatures for each month. These temperatures are used to calculate the ambient temperature in each hour of the year (see Section 3.6), according to the following relation:

$$\vartheta_{amb}(t) = \frac{\vartheta_{amb,max}+\vartheta_{amb,min}}{2} + \frac{\vartheta_{amb,max}-\vartheta_{amb,min}}{2}\sin\left(\frac{2\pi}{24}(t-7)\right) \qquad \text{(Eq. 3)}$$

where $\vartheta_{amb}(t)$ is the ambient temperature at the hour t,[°C];

$\vartheta_{amb,max}$ and $\vartheta_{amb,min}$ are the averages of the highest and of the lowest daily temperatures respectively, [°C]. A pair of average temperatures is defined for each month and for each geographical location (see Table 2 in Appendix A).

The ambient temperatures are used to estimate the yearly profile of the soil temperature (see formula from (Kusuda, 1975)), necessary to calculate the heat losses from the network, the performance of the individual cooling machines in case of conventional DH and the central chiller/cooling tower operation in case of FLEXYNETS.

Related to the ambient temperature profile during the year is the European heating index (EHI). Values for this parameter were retrieved from (Frederiksen, 2013) for the Northern, Central and Southern Europe and are listed in Table 2 in Appendix A. An exact definition of the EHI is out of the scope of this manual: for the use of the Excel tool it is sufficient to know that, assuming the same level of energy costs, optimized heat supply and same indoor temperatures, etc., the heat demand for space heating should be proportional to this index (hence Eq. 1 holds true). For more information on the EHI, the reader should refer to (Werner, 2006).

Beside supplying heat for space heating purposes, a DH/FLEXYNETS network should cover the heat demand for domestic hot water preparation. The fractions of SH, DHW compared to the total heat demand can be defined in this worksheet, if they differ from the default values (see Table 2 in Appendix A) which are based on (European Commission, 2016; Figure 2-3).

3.3.2 Temperature levels on the consumer side and machine efficiency

Regarding the temperature levels of the heating and cooling loads, these are defined by the forward and return temperature of the SH and space cooling system. If not edited by the user, these temperatures are assumed to be 50 °C and 30 °C for the SH systems, and 10 °C and 15 °C for the space cooling system. These temperatures enter in the formulas determining the COP and EER of the reversible heat pumps in FLEXYNETS and individual cooling machines in conventional DH (Eq. 7 and Eq. 11). It should be noted that the temperature for the DHW are not specified, hence the COP and other temperature-dependent quantities are calculated based on the temperatures of the SH and space cooling systems.

In this worksheet, the user defines the machine efficiency of the heat pumps in heating and cooling mode, as well as that of the individual cooling machines (η_{HP} in Eq. 10).

3.3.3 Other temperature parameters

In this worksheet —and in case a FLEXYNETS system is investigated— the user can also edit the default value of temperature difference along the evaporator of the reversible heat pumps in heating mode , that along the condenser of the heat pumps in cooling mode. It should be noted that, for the temperature difference along the evaporator of the heat pumps in heating mode, two values can be specified: a temperature difference for when the FLEXYNETS network is operated with a higher supply temperature (e.g. in heating mode) and a temperature difference when the network operates with a lower supply temperature (e.g. in cooling mode). When the network operates at higher temperature (e.g. $\vartheta_{DH,s} > 15$ °C), there is no risk of freezing at the outlet of the evaporators of the heat pumps and the temperature difference along the evaporator should be chosen as large as possible (e.g. 10 °C), compatible with the characteristics of the heat pump. When the cooling demand is dominant, it may be reasonable to operate the network as a district cooling network at low temperature (e.g. $\vartheta_{DH,s} < 10$ °C). However, this may cause freezing the outlet of the evaporators of the heat pumps in heating mode, if the temperature difference is kept the same. Hence, a lower temperature difference can be defined. The user must also define the supply temperature limit below which, this lower temperature difference is to be used.

In this worksheet the user can also redefine the default value of the temperature difference between cooling tower and ambient temperature (Eq. 13), of the temperature drop across the cooling tower (Eq. 14), of the minimum temperature difference across the two sides of heat exchangers (Eq. 8 and Eq. 9) and of the minimum temperature difference between condenser of the individual cooling units and ambient temperature (Section 3.5).

3.4 “Network” worksheet

In the worksheet “Network” the distribution network is sized in terms of length and pipe diameters. Secondly, the investment cost for its installation, the required pumping capacity and the heat losses from the network pipes are evaluated.
The length of the distribution network is estimated based on the composition of urban area (see Section 3.1) and on its resulting plot ratio, according to Eq. 4 (Persson, 2011).

$$\begin{cases} e = A_B/A_L \\ w = 61.8\, e^{-0.15} \\ L = A_L/w \end{cases} \qquad \text{(Eq. 4)}$$

where e is the plot ratio, [-];
A_B is the building space area, [m^2];
A_L is the land area, [m^2];
w is the effective width, [m];
L is the total trench length of the distribution network, [m];

Besides the main distribution pipes, each consumer is assumed to be connected to the main network by 12+12 m of supply/return service pipes.

While the length of the network depends on the distribution of the building space area in the corresponding land area, the diameters of the network pipes are determined by the maximum expected flow rate and by the constraints on the maximum velocity and/or pressure drop gradient accepted in the pipes. The design pressure drop gradient specified by default in the Excel tool is 100 Pa/m along each single pipe, while the maximum recommended fluid velocities depend on the pipe diameter and are listed in Table 4 in Appendix B.
The Excel tool calculates the maximum expected flow rate differently, depending on the type of network. In case of conventional DH, the sum of the peak heating demand of the consumers and the network heat losses determine immediately the amount of thermal power that the network needs to carry. It should be noted that the heat losses used here are a preliminary estimate defined by the user, and not the actual heat losses. The reason why the actual heat losses cannot be used here is that this would create a circular reference in Excel, as the actual heat losses depend on the pipe diameters. Consequently, after inserting/editing all the relevant inputs, the user should check that this first estimate of heat losses is in agreement with the actual heat losses (see later in this Section).
Knowing the peak thermal power carried by the network and the difference between supply and return temperature, the maximum flow rate for which the network is to be sized is given by Eq. 5. A safety factor (≥1) can additionally be defined to oversize the network.

$$\dot{V}_{max} = \frac{\dot{Q}_{max}}{\rho\, c_p\, \Delta T} \qquad \text{(Eq. 5)}$$

where $\dot{V}_{max}$ is the maximum flow rate in the network, [m^3 s^{-1}];
$\dot{Q}_{max}$ is the peak thermal power carried by the network, [MW];
ρ is the density of the heat carrier fluid, [kg m^{-3}];
c_p is the specific heat of the heat carrier fluid, [MJ kg^{-1} K^{-1}];
ΔT is the difference between supply and return temperature, [K].

On the other hand, in a FLEXYNETS network supplying both heating and cooling consumers it is not possible to calculate the total flow rate from the net thermal power carried by the network. The total flow rate in the network can be calculated as the sum of the flow rates that the single heat pumps (both in heating and cooling mode) withdraw simultaneously from the network (see Section 3.6.3 for more details). The highest sum of these flow rates —possibly corrected with a safety factor (≥1)— is chosen as the maximum flow rate that the network needs to be sized for.

Fixed the constraints for velocity and/or pressure drop along the pipes, the pipe diameter D_{max} needed to carry the maximum flow rate is determined. This choice implicitly assumes that the entire network flow is pumped from a single DH plant. However, the network pipes have different diameters depending on their position in the branched structure of the network, as it is reasonable to assume that pipes closer to the DH plant have larger diameters. To estimate the fractions of the network pipe length corresponding to the different diameters, the diameter D_{max} is scaled based on the pipe diameter distribution retrieved from examples of DH network (Jensen, 2016). The pipe diameter distribution assumed by default in the Excel tool is shown in Table 6 in Appendix B. The pipe diameters are selected from standard pipe sizes available from pipe manufacturers (see Table 4 in Appendix B).

Obviously, the approach described above is a strong simplification of how a distribution network is designed. A precise sizing of the network, such as that presented in (Jensen, 2016), is out of the scope of the Excel tool and would require information on the position and the heat load of each consumer. Hence, a different pipe diameter distribution can be defined by the user, if he has information on the network layout.

When the pipe length of each pipe diameter is known, the investment cost of the distribution network, the pipe heat losses and the pumping power can be evaluated. The total installation cost for the network is estimated based on the price assumptions presented in Table 4 in Appendix B, depending on the type of soil to be excavated and the insulation class of the pipes. The insulation class also affects the heat losses, which are calculated based on the heat loss coefficients specified in

Table 5 in Appendix B. Finally, the required pumping capacity ($W_{pump,max}$) is calculated, assuming that in full load conditions a flow rate causing the design pressure drop gradient flows in each size of pipes. The hydraulic power dissipated due to friction losses is increased by 10 %, to account for minor losses in bends, tee-junctions, etc. The efficiency of the pump (η_{pump}) is assumed to be 70 %, unless otherwise redefined by the user.

3.5 “Technologies” worksheet

The “Technologies” worksheet contains the assumptions on costs and emissions for different DH plant technologies (Rambøll, 2016), DH substations (Danish Energy Agency, 2017), heat pumps (Danish Energy Agency, 2017) and cooling machines (Dittmann, 2016), as well as fuels and electricity prices (Rambøll, 2016; Eurostat, 2017). Additionally, this worksheet calculates the installation costs, operation costs and emissions based on the installed capacity and energy usage of the different technologies, which are calculated according to what described in Section 3.6.

The following information is given for each technology.

- **Investment cost**. This represents the total costs of establishing the technology. In case of DH plants, the infrastructure and connection costs, i.e. electricity, fuel and water connections inside the premises of a plant, are also included. The investment cost is expressed per unit capacity of the considered technology. In case of capacities very different from those for which the investment costs are stated, the effect of economies of scale should be considered.

The technology catalogues used to develop the Excel tool provide the investment costs per unit of useful power output. However, the useful power output of heat pumps and cooling machines depends on the COP/EER of the machine (also stated in the catalogues), which is function of the temperature levels between the machine operates. As the temperatures levels within the FLEXYNETS differ from the conventional temperatures used by standard heat pumps, the catalogued investment cost per unit of useful energy output was converted in investment cost per unit of electric power of the compressor, so to make it independent of operating temperatures.

From the investment cost, the annualized capital cost of the investment is calculated by the annuity loan down-payment formula (Eq. 6), using the technical lifetime of the technology as investment lifetime and a user-defined interest rate (3 % by default). Inflation is neglected, and constant price level is assumed.

$$P = \frac{r\,PV}{1-(1+r)^{-n}} \qquad \text{(Eq. 6)}$$

where P is the annualized capital cost of investment, [€];
r is the yearly interest rate, [%];
PV is the present value of the total investment, [€];
n is the investment lifetime, [year].

- **Fixed O&M cost**. This is the component of the O&M cost which needs to be covered, regardless of whether/how much the unit is operated. Therefore, it can be expressed as a yearly cost (or yearly cost per unit capacity), and not per unit of produced (or consumed) energy. It includes for example administration, staff, payments for O&M service agreements, property tax, insurance, expenses necessary to keep the plant operating within the scheduled lifetime.

- **Variable O&M cost**. This is the component of the O&M cost which is proportional to the actual use of the technology. For an energy conversion plant/machine, this cost is usually expressed as cost per unit of produced (or consumed) energy. The variable O&M cost includes consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, spare parts and output related repair and maintenance. Conversely, fuel costs are not included.

  Both fixed and variable O&M costs often vary over time, increasing with the ageing of the plant/machine. So, the stated O&M costs are to be interpreted as average values over the technical lifetime of the considered technology.

- **Technical lifetime**. It is the expected time for which a plant/machine can be operated within, or acceptably close to, its original performance specifications, provided that normal operation and maintenance takes place. The technical lifetime is a theoretical value inherent to each technology, based on experience. In real life, different plants of the same technology may operate for shorter or longer times, depending on the number of hours of operation, start-ups, reinvestments made over the years, etc.

- **Energy efficiency**. It is defined as the ratio between the useful energy output and the energy input. If the energy source in input is a fuel, the lower calorific value is used.

  For compression heat pumps —regardless of whether they operate in heating or cooling mode— we define as COP the ratio between the amount of thermal power rejected at the condenser (i.e. the thermal power released by the machine to the heat sink) and the electric power absorbed by the heat pump. The COP is strongly affected by the temperature at the evaporator (heat source) and at the condenser (heat sink). In an ideal reversible heat pump, the COP depends solely on these temperatures and is calculated through Eq. 7, which gives the Carnot-COP.

$$COP_{Carnot} = \frac{\dot{Q}_{cond.}}{W_{HP}} = \frac{T_H}{T_H - T_L} \qquad \text{(Eq. 7)}$$

where COP_{Carnot} is the Carnot-COP for a reversible heat pump, [-];
$\dot{Q}_{cond.}$ is the thermal power released by the heat pump to the heat sink, [MW];
W_{HP} is the electric power absorbed by the heat pump, [MW];
$T_{H\ (\mathrm{or}\ L)}$ is the condensing (or evaporating) temperature of the refrigerant fluid, [K].

In the Excel tool, the condensing and evaporating temperature are calculated through Eq. 8 and Eq. 9 respectively.

$$T_H = T_{cond.,out} + \Delta T_{HX} \qquad \text{(Eq. 8)}$$

$$T_L = T_{evap.,out} - \Delta T_{HX} \qquad \text{(Eq. 9)}$$

where $T_{cond.,out\ (\mathrm{or}\ evap.,out)}$ is the outlet temperature of the heat sink (or heat source) fluid at the condenser (or evaporator) of the heat pump, [K];
ΔT_{HX} is the minimum temperature difference between the hot side and cold side of the heat exchangers, [K]. Unless otherwise specified by the user, this value is set to 2.5 K.

In the real world any heat pump has inefficiencies. Mechanical components such as compressors, pumps and valves do not operate with an efficiency of 100 %. Additionally, there are heat losses and temperature differences across the heat exchangers. Consequently, the actual COP of a heat pump is always much lower than the Carnot-COP. In the Excel tool the actual COP is calculated correcting the Carnot-COP, as shown in Eq. 10.

$$COP = \frac{\dot{Q}_{cond.}}{W_{HP}} = COP_{Carnot} \cdot \eta_{HP} \qquad \text{(Eq. 10)}$$

where η_{HP} is the efficiency of the heat pump, [-].

For heat pumps in cooling mode and for cooling machines in general, it is more common to express the efficiency in terms of *EER* (Energy Efficiency Ratio), which —for an ideal machine— is defined by Eq. 11. The EER of an actual machine is then defined correcting the Carnot-EER through a machine efficiency, as shown in Eq. 12.

$$EER_{Carnot} = \frac{\dot{Q}_{evap.}}{W_{HP}} = COP_{Carnot} - 1 \qquad \text{(Eq. 11)}$$

$$EER = \frac{\dot{Q}_{evap.}}{W_{HP}} = EER_{Carnot} \cdot \eta_{HP} \quad \text{(Eq. 12)}$$

where $\dot{Q}_{evap.}$ is the thermal power removed by the heat pump from the heat source, [MW];
W_{HP} is the electric power absorbed by the heat pump, [MW]

The value of η_{HP} should be chosen so that the resulting COP (or EER) is in agreement with the values reported in the performance map of the machine which is assumed to be used in the system. Unless otherwise specified by the user, the Excel tool assumes 49 % as heat pump efficiency. This value was determined comparing the nominal COPs of a reversible water/water heat pump (Aermec, 2012) with the Carnot-COPs calculated at the same temperature levels. This specific machine was chosen, because it is the same model which is installed in the pilot laboratory at EURAC, partner in the FLEXYNETS project (Cozzini, 2018).

The same approach was used to evaluate the EER of the central chiller in a FLEXYNETS system and of the individual cooling machines in case of conventional DH. The central chiller is assumed to be a water/water chiller, operating between the network temperature level on the evaporator side and a second water circuit at higher temperature on the condenser side, which is then cooled by a cooling tower. Unless otherwise specified by the user, the temperatures between which the water circuit operates are given by:

$$T_{cond.,in} = T_{tower.,out} = T_{amb} + 5\ \mathrm{K} \quad \text{(Eq. 13)}$$

$$T_{cond.,out} = T_{tower,in} = T_{cond.,in} + 5\ \mathrm{K} \quad \text{(Eq. 14)}$$

The condensing temperature of the refrigerant fluid in the central chiller is given by replacing Eq. 14 in Eq. 8. The central chiller efficiency is η_{HP}=55 %, unless otherwise specified.

The individual cooling machines use a condensing temperature equal to the ambient temperature increased by a default ΔT of 7.5 K, and a machine efficiency η_{HP} of 49 %, unless otherwise specified.

Finally, the performance of the cooling tower is expressed in terms of amount of electricity required by pumps and fans to dissipate a certain amount of heat. Unless otherwise specified, this performance is assumed to be 0.02 MWh_{el}/MWh_{heat}.

- **Fuel**. It represents the energy source in input for each technology. Each fuel is characterized by a price (tax included). For electricity two prices can be defined: one for private households and the other for industrial consumers. The first is for example used when calculating the electricity cost for running the individual cooling machines in case of conventional DH, the second is used for electricity consumptions of the central plant, such as for pumping purposes in the distribution network. The electricity price assumed for the reversible heat pumps installed at the customers' premises in a FLEXYNETS system can be either the household customer's price or the industrial customer's price, depending on the business model assumed, i.e. on whether the heat pumps are considered property of the customers or part of the distribution network. Unless otherwise specified, the industrial customer's price is used.

- **Emissions.** For the DH plant technology, the Excel tool evaluates the yearly emissions of the following greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The emissions factors are expressed in terms of mass of the considered GHG per unit energy of fuel. The emission factors for CH_4 and N_2O are function of the DH plant technology, while that for CO_2 depends only on the type of fuel (Rambøll, 2016). When the fuel is electricity, the emission factors of CH_4 and N_2O are considered null, while that of CO_2 is assumed equal to 202 kg/MWh, average value for Denmark in 2015 (Sveinbjörnsson, 2018).

To compare the GHG emissions of different scenarios, the yearly emissions of carbon dioxide equivalents (CO_2eq) are determined through Eq. 15.

$$\text{Emission of CO}_2\text{eq} = \sum_i \left(EF_i \; GWP_{100,i} \right) \cdot Q_f \quad \text{(Eq. 15)}$$

where EF_i is the emission factor of the greenhouse gas i, [kg MWh^{-1}];

$GWP_{100,i}$ is the global warming potential over 100 years of the gas i, [-]. The GWP_{100} of CH_4 is 28, that of N_2O is 265 and that of CO_2 is 1 (Myhre, 2013).

Q_f is the amount of fuel used (see Section 3.6.3), [MWh].

Because emission factors can change from country to country —which is especially true for electricity— they can be redefined by the user. A list of the emission factors of CO_2eq for consumed electricity in the EU-28 countries is found in (Moro, 2017).

It must be noted that prices of energy technologies, fuels and electricity may vary from country to country and over time. Hence, the user can modify them, so that they are representative of the case study under investigation.

3.6 "Hourly Analysis" worksheet

As seen in Section 3.4 and 3.5, the full load conditions determine the size and hence the investment cost of system components. On the other hand, the hour-by-hour loads are necessary to evaluate the actual operation of the components, fuel/electricity consumption and costs of operation. It is then of key importance to determine both the installed capacities of the different system components and the hourly energy balances. These quantities are calculated in the worksheet "Hourly Analysis".

3.6.1 Listed variables

The worksheet receives in input the hourly heating and cooling demands, the amounts of available waste heat, ambient and soil temperatures. Based on these boundary conditions, all other quantities are calculated. The variables for which hourly values are listed in this worksheet are the following:

- aggregated heating/cooling demands from the customers ($Q(t)$ in Eq. 2);
- amount of waste heat available and amount which is actually used for each of the different waste heat sources;
- aggregated energy exchanged between distribution network and substations. In case of conventional DH, this is equal to the heating demand; in case of FLEXYNETS, this is divided between the heat exchanged at the evaporator of the heat pumps in heating mode (Eq. 24) and the heat exchanged at the condenser of the heat pumps in cooling mode (Eq. 25);
- aggregated flow rate drawn by the substations. In case of FLEXYNETS, this is divided between the cumulated flow rate drawn by the heat pumps in heating mode and that drawn by the heat pumps in cooling mode (Eq. 26);

- ambient temperature (Eq. 3);
- supply and return temperature of the distribution network;
- heat losses/gains from the distribution network pipes;
- net heat load of the distribution network (Eq. 16 and Eq. 17);
- electricity consumption of the pump of the distribution network (Eq. 27);
- COP and/or EER of heat pumps, central chiller and individual cooling machines (Eq. 10 and Eq. 12);
- electricity consumption of heat pumps, central chiller and cooling machines;
- heat removed from the network at the evaporator of the central chiller;
- heat to be dissipated by the cooling tower.

3.6.2 Installed capacities

The peak power that each plant/machine needs to provide determines the capacity to be installed and hence its investment cost (Section 3.5). So, this section describes how the installed capacity of each plant/machine is determined.

In case of conventional DH, the peak thermal power carried by the network determines the size of the central heating plant (base-load heater and back-up heater), as it was for the network pipe diameters in Section 3.4. The minimum capacity which must be installed for the base-load heater is the maximum value assumed throughout the year by the expression Eq. 16. This minimum installed capacity can be increased by the user through a safety factor (≥1).

$$\dot{Q}_{DH}(t) = \dot{Q}_{dem.}(t) + \dot{Q}_{loss}(t) - \dot{Q}_{w}(t) - \eta_{pump}\, W_{pump}(t) \qquad \text{(Eq. 16)}$$

where $\dot{Q}_{DH}$ is the net load of the distribution network, [MW];
$\dot{Q}_{dem.}$ is the cumulated heat demand of the consumers connected to the DH network, [MW];
$\dot{Q}_{loss}$ is the thermal power of heat losses from the network, [MW];
$\dot{Q}_{w}$ is the total thermal power injected into the network from the waste heat sources, [MW];
η_{pump} is the efficiency of the network pump, [%];
W_{pump} is the electric power consumed by the network pump, [MW].

The capacity of back-up heater is set as fraction of the capacity of the base-load heater (by default this fraction is 20 %). So, the back-up heater is only assumed for redundancy and does not operate, as the base load heater and the waste heat sources cover the entire peak demand. Consequently, the back-up heater should have a low investment cost, while the marginal cost of operation is irrelevant, as this will not affect the economics of the system.

The cooling demand in case of conventional DH is covered by individual vapor-compression cooling machines (see Section 1). The installed capacity of the cooling machines is expressed in terms of electric capacity, to make it independent of the temperature levels (see “Investment cost” in Section 3.5). The peak electric demand of the cooling machines of all the buildings can be estimated in two alternative ways. In the first method, the user specifies the peak electric demand of the cooling machine of the single building. The cumulated peak demand is given by the product of the peak demand of the single building and the number of cooling machines, which —unless otherwise defined by the user— is equal to the number of buildings connected to the DH network. The second method consists of correcting the cumulated peak electric demand of the cooling machines resulting from the load profiles (Section 3.2), by dividing it by a user-defined diversity factor. The diversity factor takes into account the fact that the highest sum of powers coincidentally delivered by the machines of a system is still lower than the sum of the installed powers of the machines, unless there is a perfect simultaneity in their operation.

Finally, the installed capacity of the cooling machines is given by the peak electric demand of all the buildings, conservatively corrected by a safety factor (≥1).

The first method of dimensioning is preferable, when the user knows which size of machine is going to be installed in the buildings, also based on the sizes of the machines available on the market. The second method is more suitable when the user does not have information on the installed power required by the single buildings.

The same two methods are available for sizing the heat exchangers of the substations in case of conventional DH. In this case, typical values of diversity factors for conventional DH are in the range 0.4-0.6 (Winter, 2001; Vestergaard, 2012).

In case of FLEXYNETS, the simultaneous presence of heating and cooling consumers makes the sizing of the central plant less straightforward compared to conventional DH. In this case the net load of the distribution network is given by Eq. 17. The installed capacity of the base-load heater should be no lower than the maximum positive value of the net load (Eq. 18).

$$\dot{Q}_{DH}(t) = \dot{Q}_{evap.}(t) + \dot{Q}_{loss}(t) - \dot{Q}_{cond.}(t) - \dot{Q}_{w}(t) - \eta_{pump}\, W_{pump}(t) \qquad \text{(Eq. 17)}$$

$$\dot{Q}_{heater} = \max\left(\dot{Q}_{DH}\right)^{+} \qquad \text{(Eq. 18)}$$

$$\dot{Q}_{chiller} = \max\left(-\dot{Q}_{DH}\right)^{+}\Big|_{chiller\ op.} \qquad \text{(Eq. 19)}$$

where $\dot{Q}_{DH}$ is the net load of the distribution network, [MW];

$\dot{Q}_{evap.\ (\mathrm{or}\ cond.)}$ is the total thermal power transferred between the network and the evaporators (or condensers) of the reversible heat pumps in heating (or cooling) mode, [MW];

$\dot{Q}_{loss}$, $\dot{Q}_{w}$, η_{pump} and W_{pump} have the same definition as in Eq. 16;

$\dot{Q}_{heater\ (\mathrm{or}\ chiller)}$ is the installed capacity of the base-load heater (or central chiller), [MW];

superscript + denotes that only positive values of the quantity in brackets are considered;

subscript $chiller\ mode$ refers to when the central chiller is in operation.

As for conventional DH, the capacity of back-up heater is assumed equal to 20 % of the capacity of the base-load heater.

The minimum negative value of the net load represents the minimum capacity of the central chiller (Eq. 19), provided that the conditions for its operation are fulfilled. On the other hand, the installed capacity of the cooling tower is given by:

$$\dot{Q}_{tower} = \max\left(\max\left(\frac{1+EER}{EER}\left(-\dot{Q}_{DH}\right)^{+}_{chiller\ mode}\right), \max\left(-\dot{Q}_{DH}\right)^{+}_{tower\ mode}\right) \quad \text{(Eq. 20)}$$

where $\dot{Q}_{tower}$ is the installed capacity of the cooling tower, [MW];
EER is the Energy Efficiency Ratio of the central chiller as defined by Eq. 12, [-];
$\left(-\dot{Q}_{DH}\right)^{+}$ has the same definition as in Eq. 19, [MW];
subscript $chiller\ mode$ refers to when the central chiller is in operation;
subscript $tower\ mode$ refers to when the cooling tower alone (without the central chiller) is in operation.

The cooling tower operates alone (without the central chiller), when the ambient temperature is sufficiently low compared to the network supply temperature. More specifically, the condition for this operation mode is given by Eq. 21:

$$\vartheta_{amb} \leq \vartheta_{DH,s} - 5\ \mathrm{K} \quad \text{(Eq. 21)}$$

where ϑ_{amb} is the ambient temperature, [°C];
$\vartheta_{DH,s}$ is the network supply temperature, [°C].

If the condition Eq. 21 is not fulfilled, then the central chiller turns on and transfers the required amount of heat from the distribution network to a second water loop operating at higher temperature (between the temperatures given by Eq. 13 and Eq. 14). The heat is hence removed from the water loop through the cooling tower.
Because the peak heating/cooling demands may prove to be underestimated, when calculated from the load profiles, the user can insert a safety factor (≥1) to correct the result of Eq. 18, 19 and 20, and so increase the installed capacity of these units.

The installed capacity of the reversible heat pumps in case of FLEXYNETS can be estimated in two alternative ways, similarly to what described for the individual cooling machines in case of conventional DH. In the first method the user specifies the peak electric power absorbed by the heat pump of a single building. The cumulated peak power is then the product of the peak demand of the single heat pump building and the number of the buildings connected to the DH network. The second method consists of using the peak electric power of the heat pumps resulting from the load profiles and a user-defined diversity factor. In this case, the electric power (W_{HP}) absorbed by the heat pumps in heating and cooling mode can be made explicit in Eq. 10 and Eq. 12 respectively and hence calculated using Eq. 24 and Eq. 25 as inputs. The highest sum of these two electric powers throughout the year (see Eq. 22) is corrected by a user-defined diversity factor and represents the installed electric capacity of the reversible heat pumps.

$$W_{HP,installed} = \max\left(W_{HP,h}\,(t) + W_{HP,c}(t)\right) \quad \text{(Eq. 22)}$$

3.6.3 Hourly energy balances

The energy output from the base-load heater for both conventional DH and FLEXYNETS is calculated by

$$Q_{heater} = \sum^{8760\ h} \dot{Q}_{DH}(t) \quad \text{(Eq. 23)}$$

where Q_{heater} is the energy output of the base-load heater, [MWh];

$\dot{Q}_{DH}(t)$ is net load of the distribution network on an hourly basis [MW], which is given by Eq. 16 in case of conventional DH, and by the positive values of Eq. 17 in case of FLEXYNETS.

Through the efficiency of the chosen technology the fuel input is calculated and consequently the corresponding operation costs and GHGs emissions.

Regarding the individual cooling machines in case of conventional DH, and the reversible heat pumps as well as the central chiller in case of FLEXYNETS, their COP/EER is determined according to what described in the subsection “Energy efficiency” in Section 3.5, as function of the operating temperatures. Based on the COP/EER of the machine and the energy demand, the electricity consumption is calculated for each hour of the year (Eq. 10 and Eq. 12).
In case of FLEXYNETS, the thermal power transferred between the heat pumps and the network is calculated through Eq. 24 and Eq. 25.

$$\dot{Q}_{evap.} = \dot{Q}_{dem.,h}\left(1 - \frac{1}{COP}\right) \qquad \text{(Eq. 24)}$$

$$\dot{Q}_{cond.} = \dot{Q}_{dem.,c}\left(1 + \frac{1}{EER}\right) \qquad \text{(Eq. 25)}$$

where $\dot{Q}_{dem.,h\ (\mathrm{or}\ c)}$ is the cumulated heating (or cooling) demand of the consumers, [MW];
$\dot{Q}_{evap.\ (\mathrm{or}\ cond.)}$ is the total thermal power transferred between the network and the evaporators (or condensers) of the reversible heat pumps in heating (or cooling) mode, [MW];
COP is the COP of the reversible heat pump in heating mode, [-],
EER is the EER of the reversible heat pump in cooling mode, [-].

The cumulated flow rate drawn from the network by the heat pumps in heating (or cooling) mode is given by Eq. 26:

$$\dot{V}_{evap.(\mathrm{or}\ cond.)} = \frac{\dot{Q}_{evap.(\mathrm{or}\ cond.)}}{\rho\ c_p\ \Delta T_{evap.(\mathrm{or}\ cond.)}} \qquad \text{(Eq. 26)}$$

where $\dot{V}_{evap.(\mathrm{or}\ cond.)}$ is the cumulated flow rate in the evaporators (or condensers) of the heat pumps in heating (or cooling) mode, [$m^3\ s^{-1}$];
$\Delta T_{evap.(\mathrm{or}\ cond.)}$ is the difference in water temperature along the evaporator (or condenser) of the heat pumps in heating (or cooling) mode, [K].

The total flow rate in the distribution network is then the sum of these two cumulated flow rates. The Excel tool assumes that the flow rate circulating in the network determines the electric power absorbed by the network pump through the affinity law for centrifugal pumps (Eq. 27) (Gülich, 2010).

$$W_{pump} = W_{pump,max} \cdot \left(\frac{\max(\dot{V}_{min}, \dot{V})}{\dot{V}_{max}}\right)^3 \qquad \text{(Eq. 27)}$$

where W_{pump} is the electric power consumed by the network pump(s), [MW];
$\dot{V}$ is the total flow rate in the network, [$m^3\ s^{-1}$];
$\dot{V}_{min}$ is the minimum flow rate which is assumed to be circulated in the distribution network, [$m^3\ s^{-1}$]. For conventional DH this is assumed to be 20 % of the maximum flow rate (Frederiksen,

2013; Figure 10.26), while in a FLEXYNETS system this is assumed to be 10 % of the maximum flow rate.

$\dot{V}_{max}$ is the maximum flow rate circulating in the distribution network, [m^3 s^{-1}], i.e. the highest value of the total flow rate throughout the year. This is the flow rate which is used to size the diameters of the network pipes, as described in Section 3.4.

$W_{pump,max}$ is the pumping power [MW] corresponding to the flow rate $\dot{V}_{max}$, and is calculated as described in Section 3.4.

Regarding the cooling tower, the heat which this needs to dissipate is the condensing heat of the central chiller (Eq. 25). Based on this and on the performance of the cooling tower (see "Energy efficiency" in Section 3.5), the electricity consumption is calculated.

3.7 "PTES" worksheet

In the worksheet "PTES" a simplified analysis on how the presence of a water pit thermal energy storage (PTES) connected to one of the waste heat sources affects the sizing and the performance of the system. The PTES aims at increasing the amount of waste heat recovered by the system and decreasing the need of energy from the central heater. The analysis is available for both conventional DH and FLEXYNETS. For a more detailed analysis on the use of large-scale TES in DH/FLEXYNETS networks, the interested reader may refer to the deliverable (Sveinbjörnsson, 2018), produced within the FLEXYNETS project.

The heating demand profile and the availability profile of waste heat are not necessarily similar throughout the year. Most of the heating demand occurs in winter, while the availability of waste heat depends on the type of waste heat source. Waste heat from industrial processes may be almost constant throughout the year, with no significant variation from month to month. On the other hand, condensing heat dissipated by cooling processes is likely to be larger in summer, when the ambient temperature is higher. A long-term TES may be used to store excess waste heat in summer for later use at the beginning of the heating season.

Among the different types of long-term TES (see Sveinbjörnsson, 2018), the Excel tool considers only PTES technology, because this is currently the most implemented solution, when large storage capacities are needed.

To run the macro, the user must have specified from the appropriate dropdown menu in the "Inputs" worksheet the waste heat source to which she/he wants the PTES to be connected to. If this is the case, she/he just needs to press the grey button "PTES sizing".

Because both investment cost per unit volume and relative heat losses of a PTES decrease for increasing sizes, by default the PTES is sized to be as large as possible, but having as upper boundary the lower between the two following constraints. The first constraint is the amount of heat from the PTES-equipped waste heat source which exceeds the network heating load. A PTES with a larger capacity would never be fully charged. The second constraint is the amount of heat that the central heater would supply, if the PTES was not present (this amount is however corrected to consider the heat losses from the PTES). A PTES with a larger capacity would never be fully discharged. Alternatively, the user can specify the PTES capacity.

Based on this upper boundary, the energy content of the PTES at the end of each month is calculated through Eq. 28.

$$Q(m) = Q(m-1) \cdot (1 - U_{PTES}) + Q_{charge}(m) - Q_{discharge}(m) \qquad \text{(Eq. 28)}$$

where $Q(m)$ is the energy content of the PTES at the end of the month m, [MWh];
U_{PTES} is the heat loss coefficient of the PTES, [% month^{-1}];
$Q_{charge}(m)$ is the heat injected into the PTES during the month m, [MWh]. This is the amount of heat from the PTES-equipped waste heat source which exceeds the network net heating load (Eq. 16 and Eq. 17).
$Q_{discharge}(m)$ is the heat discharged from the PTES into the network during the month m, [MWh]. This is equal to minimum value between the PTES energy content and the amount of heat the central heater would supply during the same month, if the PTES was not present.

For the charging/discharging cycle to be repeatable every year, the energy content of the PTES at the beginning and at the end of the year must be the same. Imposing this boundary condition on Eq. 28, the profile of the storage energy content during the year is found.
To determine the size of the PTES (and hence its investment cost), not only the highest energy content throughout the year must be known, but also the temperature difference across the storage. The following assumptions regarding the temperatures in the PTES are made. The PTES is divided in two isothermal layers. The upper layer is always charged at the temperature of the waste heat source connected to the PTES. The temperature of the lower layer at the end of each month results from the mixing of the volume of the lower layer from the previous month and the cumulated volume discharged from the top of the PTES, which returns to the bottom of the PTES at the network return temperature. Assuming constant density and specific heat of the heat carrier fluid, the temperature of the lower layer of the PTES is given by (Eq. 30).

$$V_{up.}(m) = V_{up.}(m-1) \cdot (1 - U_{PTES}) + \frac{Q_{charge}(m)}{\rho\, c_p\, (\vartheta_w - \vartheta_{low.}(m-1))} - \frac{Q_{discharge}(m)}{\rho\, c_p\, \left(\vartheta_w - \vartheta_{DH,r}(m)\right)} \qquad \text{(Eq. 29)}$$

$$\vartheta_{low.}(m) = \frac{V_{low.}(m-1)\, \vartheta_{low.}(m-1) + \left(V_{low.}(m) - V_{low.}(m-1)\right)^{+} \vartheta_{DH,r}(m)}{V_{low.}(m)} \qquad \text{(Eq. 30)}$$

$$V_{PTES} = V_{up.}(m) + V_{low.}(m) \qquad \forall\, m \qquad \text{(Eq. 31)}$$

where $V_{up.}(m)$ is the volume of the upper layer of the PTES at the end of month m, [m^3];
$V_{low.}(m)$ is the volume of the lower layer of the PTES at the end of month m, [m^3];
V_{PTES} is the total volume of the PTES, [m^3];
$\vartheta_{low.}(m)$ is the temperature of the lower layer of the PTES at the end of month m, [°C];
ϑ_w is the temperature of the waste heat source connected to the PTES, [°C];
$\vartheta_{DH,r}(m)$ is the network return temperature in the month m, [°C];
the superscript + denotes that only positive values of the quantity in brackets are considered.

It should be noted that the heat loss coefficient decreases only the energy content of the PTES, not its temperature (see Eq. 29).

Based on the above-mentioned assumptions and imposing that the state of charge of the storage at the beginning and at the end of the year must be the same, the volume of the PTES can be found (Eq. 31).

Once the PTES is sized and the new energy balances are calculated, the variations in costs (reduced operation cost for the base-load heater, increased cost for purchasing waste heat and PTES-related costs) and GHGs emissions compared to the scenario without PTES are assessed. Based on the results, the user can choose in the appropriate dropdown menu whether to implement the PTES or not. The choice affects how the main results are shown in the "Summary" worksheet.
It should be noted that the presence of the PTES is assumed not to affect the installed capacity (and hence the investment cost) of the base-load heater, but only its operation cost due to the lower use of fuel.

3.8 "Summary" worksheet

Finally, a summary of the main inputs, relevant parameters and key-performance indicators is reported in the "Summary" worksheet. Two sets of values always appear, one referring to Conventional DH and the other to a FLENYNETS system. It should be noted that only the set referring to the selected type of network in the "Inputs" worksheet is relevant. The values of the other set (which is automatically greyed out) have no meaning and should be disregarded. Among the others, the summary includes:

- Yearly heating/cooling demands,
- Yearly energy production/consumption/exchange of the different system components, such as distribution network, waste heat sources, base-load and back-up load heaters, network pump, reversible heat pumps (only for FLEXYNETS), central chiller (only for FLEXYNETS), cooling tower (only for FLEXYNETS),
- Installed capacities of the different system components, such as base-load and back-up heaters, network pump, reversible heat pumps (only for FLEXYNETS), central chiller (only for FLEXYNETS), cooling tower (only for FLEXYNETS),
- Distribution network characteristics, such as lengths of main pipes and service pipes, heat losses/heat gains,
- Investment cost, capital cost of investment, fixed O&M costs, operation costs (variable O&M costs + fuel costs) for distribution network, network pump, base-load heater, back-up heater, reversible heat pumps (only for FLEXYNETS), central chiller (only for FLEXYNETS), cooling tower (only for FLEXYNETS)
- Cost of excess heat,
- Emissions of CO_2eq from electricity (network pump, HP, central chiller, cooling tower) and from base-load heater.

3.9 "Legend" worksheet

In this worksheet a list and description of the various abbreviations or nomenclature terms present in the Excel tool is present.

4 Nomenclature

A list of the acronyms and symbols used in this manual is reported below:

Symbol	Description	Unit
A	Area	[m^2]
COP	Coefficient of performance (of a heat pump)	[-]
c_p	Specific heat	[MJ kg^{-1} K^{-1}]
DH	District Heating	
DHW	Domestic hot water	
E	Electrical energy	[MWh]
EER	Energy Efficiency Ratio (of cooling machine)	[-]
e	Plot ratio	[-]
f	Fraction	[-]
L	Length (of the distribution network)	[m]
m	Month of the year	[-]
n	Investment lifetime	[year]
P	Annualized capital cost of investment	[€]
PTES	Pit Thermal Energy Storage	
PV	Present value of the total investment	[€]
Q	Thermal energy	[MWh]
$\dot{Q}$	Thermal power	[MW]
r	Interest rate	[%]
SH	Space heating	
t	Time	[h]
T	Temperature	[K]
U_{PTES}	Heat loss coefficient of the PTES	[% month^{-1}]
V	Volume	[m^3]
$\dot{V}$	Volume flow rate	[m^3 s^{-1}]
w	Effective width	[m]
W	Electric power	[MW]
ΔT	Temperature difference	[K]
η	Efficiency	[-]
ϑ	Temperature	[°C]
ρ	Density	[kg m^{-3}]
Subscripts		
amb	Ambient (temperature)	
B	Building (area)	
c	Cooling (mode/demand)	
cond.	Condenser of a heat pump	

$dem.$	Demand
el	Electricity
$evap.$	Evaporator of a heat pump
f	Fuel
h	Heating (mode/demand)
H	condensing (temperature) of the refrigerant fluid in a HP
in	Inlet
L	Land (area)
L	evaporating (temperature) of the refrigerant fluid in a HP
$low.$	Lower (layer, in PTES)
out	Outlet
r	Return (temperature)
s	Supply (temperature)
$up.$	Upper (layer, in PTES)
w	Waste heat

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6 Appendix A

This appendix reports the defaults parameters and load profiles assumed by the Excel which depend on the selected geographical location.

Table 1: Assumed specific heating demand for Northern Europe (Jensen, 2016; Figure 3 and Figure 35).

Settlement typology	Heating demand [GWh/km^2/y]
Low density residential	18
High density residential	50
Public	20
Light industry	18
Heavy industry	16
Other (parks, etc.)	2

Table 2: Assumed parameters depending on the geographical location.

	North Europe		Central Europe		Southern Europe		Source
Fraction of heat loss in conventional DH, [-]	0.15		0.15		0.15		Dansk Fjernvarme, 2017
Yearly SH demand/Yearly heat demand f_{SH}, [-]	0.90		0.84		0.82		European Commission, 2016
European heating index, EHI [-]	120		105		70		Frederiksen, 2013
Ambient temperature [°C]	$\bar{T}_{min}$	$\bar{T}_{max}$	$\bar{T}_{min}$	$\bar{T}_{max}$	$\bar{T}_{min}$	$\bar{T}_{max}$	From www.holiday-weather.com for Stockholm (North Europe), Stuttgart (Central Europe) and Rome (South Europe)
January	-5	-1	-2	3	3	13	
February	-5	-1	-2	6	3	14	
March	-3	3	1	11	6	17	
April	1	9	4	15	8	20	
May	6	16	8	20	13	24	
June	11	21	11	23	17	29	
July	13	22	13	24	19	32	
August	13	20	13	24	18	30	
September	9	15	10	21	16	27	
October	5	10	6	14	12	23	
November	1	4	2	7	8	18	
December	-3	1	-1	4	4	15	

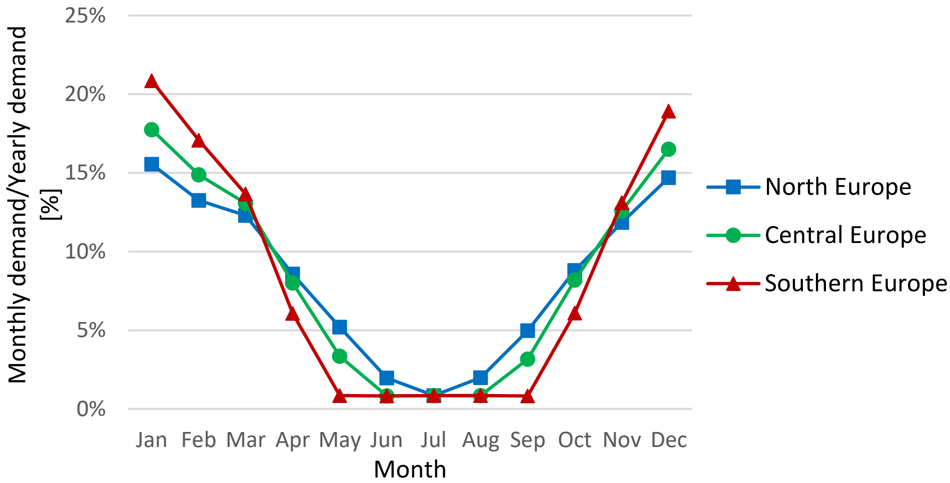

Figure 4: Default yearly load profiles for heating demand assumed in the Excel tool.

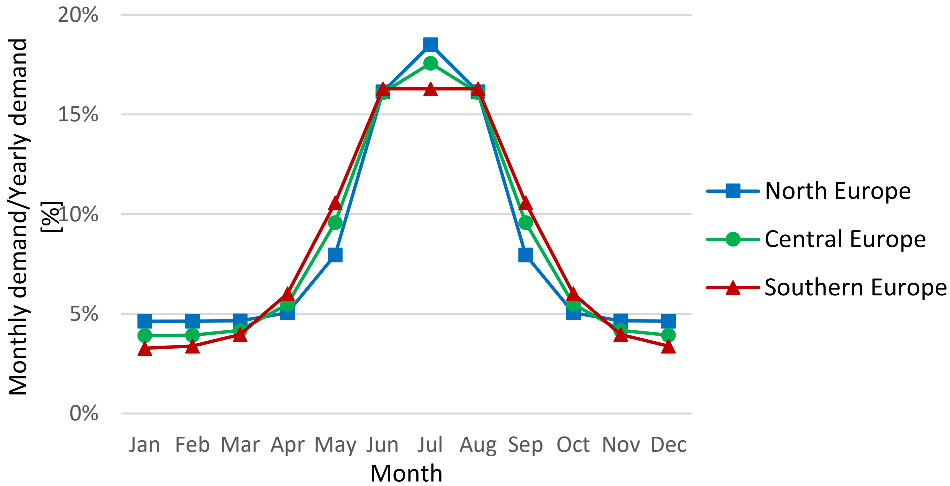

Figure 5: Default yearly load profiles for cooling demand assumed in the Excel tool.

Table 3: Assignation of the different months of the year to the available seasons, as function of the geographical location.

	North Europe	Central Europe	Southern Europe
Jan	winter	winter	winter
Feb	winter	winter	winter
Mar	winter	winter	spring/fall
Apr	spring/fall	spring/fall	summer
May	spring/fall	spring/fall	summer
Jun	spring/fall	summer	summer
Jul	summer	summer	summer
Aug	summer	summer	summer
Sep	spring/fall	spring/fall	summer
Oct	spring/fall	spring/fall	spring/fall
Nov	winter	winter	winter
Dec	winter	winter	winter

7 Appendix B

Table 4 lists the assumed material and installation prices for DH network pipes, as well as the maximum allowed velocities assumed for these pipes. The prices of the pipes were collected from a Danish manufacturer of DH pipes, while installation prices are based on Swedish experiences in ground work. The maximum velocities were assumed based on the recommendations given in (Logstor, 2017).
Table 5 lists the heat loss coefficients from pre-insulated pipes, when installed alone or in pair.
Table 6 shows the pipe diameter distribution assumed by the Excel tool, i.e. the fraction of the total length of the distribution network (service pipes are excluded) for each pipe size category.

Table 4: Prices (Jensen, 2016; Appendix A) and maximum fluid velocity for network pipes for different insulation classes.

Pipe diameter		Max. velocity [m/s]	Pipe cost: Material [€/m]				Installation cost for SERIES 3 [€/m]	
DN	D_i [mm]		SERIES 1	SERIES 2	SERIES 3	SERIES X	Paved area	Unpaved area
20	26.9	1.0	19	24	29	13	182	93
25	33.7	1.0	25	30	36	19	190	102
32	42.4	1.0	32	38	45	20	225	117
40	48.3	1.0	39	45	51	29	259	136
50	60.3	1.5	47	54	62	37	304	166
65	76.1	1.5	53	68	83	37	341	190
80	88.9	1.5	69	80	91	54	385	208
100	114.3	1.5	90	105	119	72	450	255
125	139.7	1.5	106	122	137	89	524	299
150	168.3	1.5	147	171	195	131	624	343
200	219.1	2.0	273	317	361	249	706	408
250	273	2.0	358	411	464	318	731	412
300	323.9	2.5	452	502	552	422	804	474
350	355.6	2.8	498	567	636	458	856	517
400	406.4	3.0	544	632	720	467	907	560
450	457	3.0	617	717	817	441	966	597
500	508	3.0	691	802	913	611	1026	633
600	609.6	3.0	905	1069	1233	840	1156	783
700	711.2	3.0	1185	1425	1664	1097	1313	948
800	812.8	3.0	1552	1900	2247	1429	1447	1041

Based on the installation costs for SERIES 3, an interpolation function which depends on the external pipe diameter (pipe+insulation thickness) is obtained. The installation costs for other pipe series and different external pipe diameters are obtained inserting as input in the function the corresponding external pipe diameter. The installation cost functions for paved and unpaved area are given by Eq. 32 and Eq. 33 respectively.

$$Cost = 1.7 \cdot 10^{-6}\, D_{ext}^3 - 0.0037\, D_{ext}^2 + 3.28\, D_{ext} - 149 \qquad \text{(Eq. 32)}$$

$$Cost = 1.1 \cdot 10^{-6}\, D_{ext}^3 - 0.0020\, D_{ext}^2 + 1.84\, D_{ext} - 90 \qquad \text{(Eq. 33)}$$

Table 5: Typical values of heat loss coefficients and external diameters of pre-insulated pipes (Jensen, 2016; Appendix B). The heat loss coefficient U_{pipe} refers to a single pipe lying alone, while U_{pair} refers to single pipe installed beside its return pipe.

	SERIES 1			SERIES 2			SERIES 3			SERIES X	
DN	D_o	U_{pipe}	U_{pair}	D_o	U_{pipe}	U_{pair}	D_o	U_{pipe}	U_{pair}	D_o	U_{pipe}
	[mm]	[W/(m K)]		[mm]	[W/(m K)]		[mm]	[W/(m K)]		[mm]	[W/(m K)]
20	90	0.13	0.13	110	0.11	0.11	125	0.1	0.1	67	0.21
25	90	0.16	0.15	110	0.13	0.13	125	0.12	0.12	72	0.27
32	110	0.16	0.16	125	0.14	0.14	140	0.13	0.13	83	0.29
40	110	0.19	0.18	125	0.16	0.16	140	0.15	0.14	87	0.34
50	125	0.21	0.2	140	0.18	0.18	160	0.16	0.15	102	0.37
65	140	0.25	0.24	160	0.21	0.2	180	0.18	0.17	119	0.43
80	160	0.26	0.25	180	0.22	0.21	200	0.19	0.18	134	0.46
100	200	0.27	0.26	225	0.23	0.22	250	0.2	0.19	169	0.47
125	225	0.32	0.3	250	0.26	0.25	280	0.22	0.21	196	0.54
150	250	0.38	0.35	280	0.3	0.28	315	0.25	0.23	228	0.61
200	315	0.42	0.39	355	0.32	0.3	400	0.26	0.24	291	0.63
250	400	0.4	0.37	450	0.31	0.29	500	0.25	0.25	362	0.62
300	450	0.46	0.43	500	0.35	0.33	560	0.28	0.27	418	0.70
350	500	0.45	0.42	560	0.34	0.32	630	0.27	0.26	463	0.66
400	560	0.47	0.44	630	0.35	0.33	670	0.31	0.3	511	0.78
450	630	0.47	0.44	670	0.4	0.38	710	0.31	0.33	559	0.91
500	670	0.55	0.51	710	0.46	0.43	800	0.34	0.33	623	0.86
600	800	0.56	0.52	900	0.4	0.38	1000	0.31	0.3	761	0.77
700	900	0.64	0.6	1000	0.45	0.43	1100	0.35	0.34	863	0.90
800	1000	0.73	0.68	1100	0.51	0.48	1200	0.4	0.38	965	1.02

Beside the commercially available SERIES 1, 2 and 3, a fictitious type of type was also added to the Excel too, under the name of SERIES X. This pipe series is assumed to use the same metal pipe sizes as the above-listed SERIES 1, 2 and 3, but its insulation thickness is assumed to be equal to the 1/3 of the insulation thickness of SERIES 3 pipes. The resulting external pipe diameters (pipe+insulation thickness) for SERIES X's pipes are listed in Table 5.

The cost of the pipes of SERIES X (material only) is calculated by linear extrapolation of the costs of the pipes of SERIES 1 and 3 with respect to the external pipe diameter. The resulting costs are listed in Table 4. As for the other pipe series, the installation costs for SERIES X for paved and unpaved area were calculated through Eq. 32 and Eq. 33 respectively. The heat loss coefficient for each pipe diameter of SERIES X was calculated through the conduction equation applied to cylindrical geometry, using the SERIES X's dimensions and considering only the insulation thickness as thermal resistance. The value of thermal conductivity used in the calculation was the one which gave the best fit between the tabled heat loss coefficients (Table 5) and the heat coeffiecients calculated with the same conduction equation applied to SERIES 1 and SERIES 3. The resulting heat loss coefficients for SERIES X's pipes are also listed in Table 5.

Table 6: Fraction of the total length of the distribution network (service pipes are excluded) for each pipe size category assumed in the Excel tool.

	% length [%]	D^2/D_{max}^2 [-]
Pipe size 1	43.3%	0.025
Pipe size 2	23.5%	0.043
Pipe size 3	18.4%	0.109
Pipe size 4	7.8%	0.244
Pipe size 5	4.1%	0.665
Pipe size 6	3.0%	1.0
Total	100%	