



Department of Mechanical and Aerospace Engineering

**Introduction of a thermal district energy network
design tool**

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Date: 23.08.2019

Abstract

District heating or cooling grids are an option of centrally supplying consumers with thermal energy while offering a wide range of technical and operational benefits both to the consumer as well as to the supplier. In addition to technical advantages compared to decentralised supply local thermal grids also deliver a great potential to reduce greenhouse gas emissions in comparison to conventional decentral thermal power systems. The reduction of emissions is even more the case of systems powered by heat pumps.

Designing small-scale thermal district energy grids is mostly connected to major engineering work. Often significant amounts of effort and time are invested in the first stages of design before recognising a project cannot be realised due to a lack of engineering or economic feasibility. To reduce the work spent on this first stage of design and decision making a tool for quick first designs and investment cost estimations is introduced.

The software tool developed within this thesis is supposed to help designers quickly produce first approximations of the sizes and investments for major parts of systems. The complexity of inputs is tried to be kept to a minimum, while still yielding reliable results.

Systems modelled with the software are powered by heat pumps in combination with a thermal store without the need of including conventional back-up heat sources to cover demand. The core elements modelled are the energy supply system, as well as with the piping network and circulation pumps responsible for transporting the heat from the production site to the consumers.

Calculations are based on model demand profiles along with a grid map that needs to be identified by the user outside of the tool preliminarily to running simulations. Those two inputs and some physical boundaries are handed over to the tool to generate results. For all elements designed the most important engineering parameters and investment costs are supplied to the user.

Once all necessary data is available to the user simulations can be performed within a matter of minutes to a substantially comprehensive level of detail.

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List of Abbreviations

BIHP	Building Integrated Heat Pump
CHP	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient Of Performance
csv	comma-separated values
DC	District Cooling
DE	District Energy
DH	District Heating
DHW(S)	Domestic Hot Water (Supply)
EU	European Union
GHG	Green House Gas
GIS	Geographic Information System
GUI	Graphical User Interface
HIU	Heat Interface Unit
HP	Heat pump
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LULUCF	Land use/land use change and forestry

Nomenclatures

\dot{V}	Volume flow
c_p	Specific heat capacity
ΔT	Temperature difference
D	Inner pipe diameter
f	Darcy friction factor
g	Gravitational acceleration
H	Hydraulic head
L	Pipe length
P	Power
p	Pressure
P_0	Peak power
Re	Reynolds number
T	Temperature
v_{act}	Actual flow velocity
v_{max}	Maximum flow velocity
Δp	Pressure difference
Δp_l	Pressure loss
η	Efficiency
ν	Kinematic velocity
ρ	Fluid density
ω	Roughness factor

1. Introduction

1.1. Background

All over the world people realise that changing human behaviour towards a more sustainable and preserving lifestyle in all aspects of life is of high importance. This concerns many different areas and disciplines. One specific area, which is one of the most pressing in order to mitigate climate change and preserve the Earth's atmosphere's composition is the reduction of green-house gas (GHG) emissions. A global trend towards reduced carbon emissions is manifested in several agreements on national and international basis, the most well-known being the United Nations' Paris agreement (United Nations Organization, 2015).

To reach the targets set in the Paris agreement of limiting global warming to 1.5°C and keeping the increase "well below" 2°C, reducing GHG emissions plays a crucial role. The main driving factor for climate change is those emissions. Only 25% of climate change effects can be explained by natural variability, while the other 75% are caused by anthropogenic influences mainly being GHG emissions (Crowley, 2000).

Many countries set their individual goals to achieve reductions in GHG emission. The UK for example introduced the *Climate Change Act 2008*, aiming to reduce its emissions by 80 % until 2050. It is supposed to reach this target by putting several energy policies in place (Crown, 2008).

In the European Union (EU) one of the main drivers of GHG emissions is the residential sector, as shown in Figure 1.

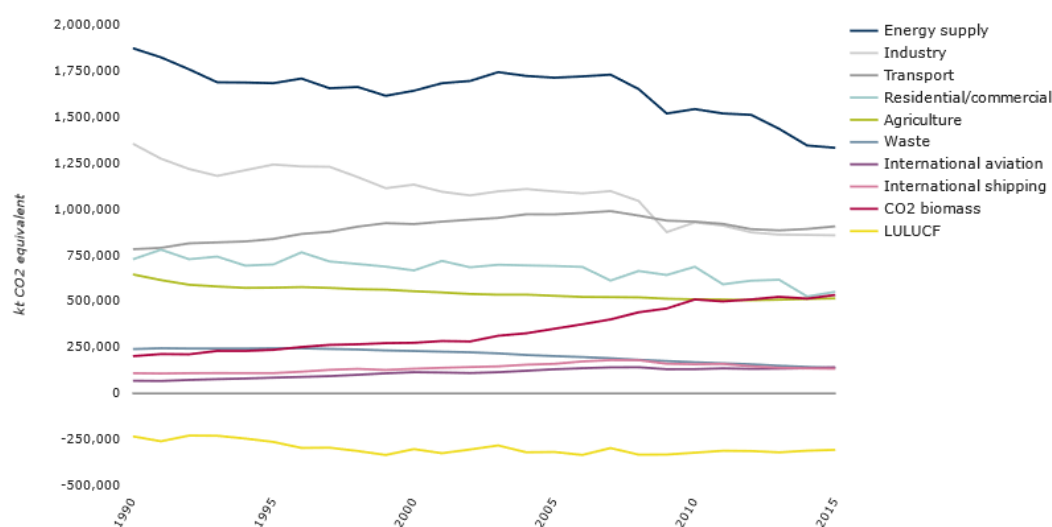


Figure 1: GHG emissions by aggregated sector in the EU. (EEA, 2018).

Energy consumption, which represents the major cause for GHG emissions within the residential sector is comprised of four main categories (Colmenar-Santos et al., 2017): Space heating, water heating, cooking and electricity. The share on the total energy consumption of these four categories is illustrated in Figure 2.

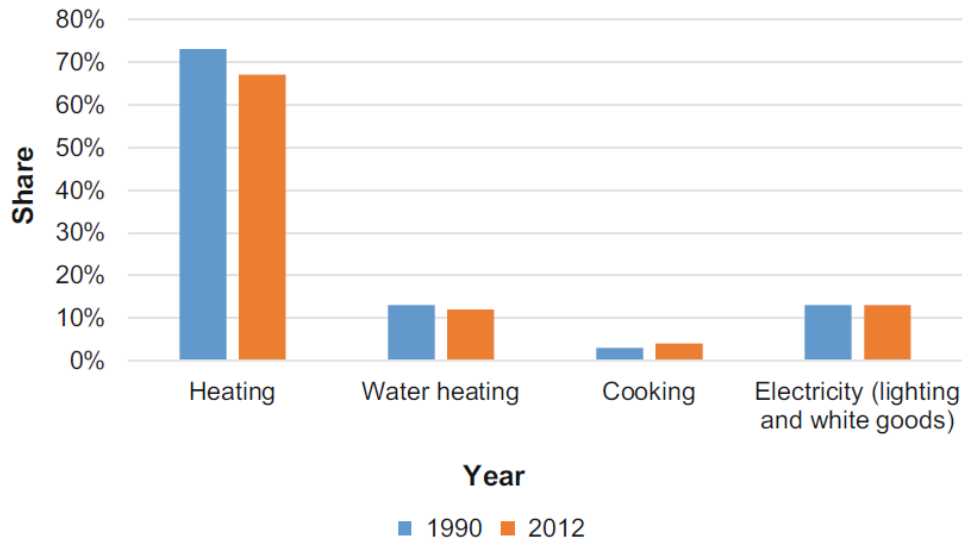


Figure 2: Energy consumption in dwellings in the EU (Colmenar-Santos et al., 2017).

Data for this diagram was originally adapted from the *Energy Technology Perspectives 2015* by Colmenar-Santos et al. (IEA, 2015).

The International Energy Agency (IEA) urges that technologies are necessary to evolve and developed green technologies need be implemented to tackle the issue of emission reduction (IEA, 2017).

One rather new possible technological solution is the implementation of district heating (DH) schemes, driven by heat pumps (HP). This thesis is dedicated to help the process of designing systems like that. By simplifying the initial design process the application of more systems with that energy source may be realised.

1.2. Aim and motivation

The aim of this dissertation is to simplify and accelerate the pre-construction process of district heating projects at multiple stages. This is done by introducing a software tool for a quick first design of the basic parameters of a DH system powered by HPs.

Several tools are available on the market for modelling grids in great detail. Most of them are based on geographic information systems (GIS) and complex database architecture in the background. One of the leading software tools on the European market for example is NetSim by Vitec Software Group. Tools like that are rather

complex and potentially need professional training before accurate simulations can be performed by the user. Those extensive simulations are also rather time consuming. The tool developed for this project is focused to make initial project design work faster. This shall be possible without the need of a lengthy work-in period on a new tool and to a simple and intuitive user interface.

As the physics behind DH and district cooling (DC) are the same to a certain degree of detail, the algorithm also works for the design of DC systems. Systems may be referred to as district energy (DE) systems in the following.

HPs can also be used for cooling purposes, which makes the tool usable for DC and DH system simulations. The Chartered Institution of Building Services Engineers (CIBSE) gives an overview of the different process steps within the realisation of a district energy scheme (Figure 3) in the *Heat networks: Code of Practice for the UK* (Woods et al., 2015).

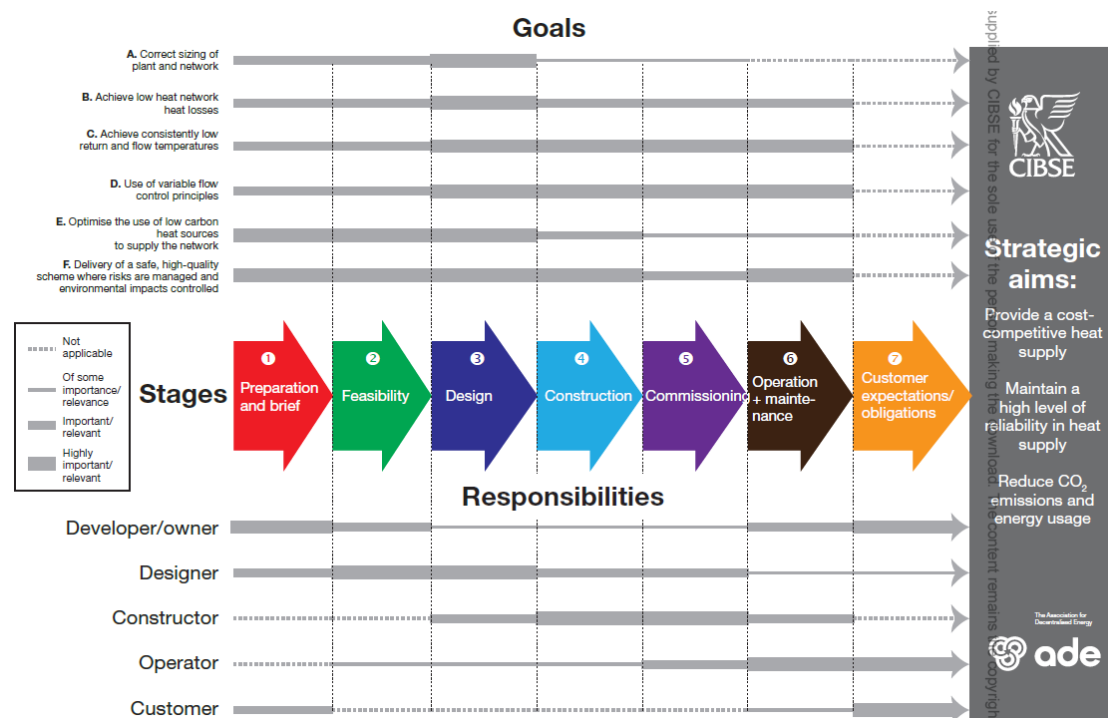


Figure 3: Stages of a DH system (Woods et al., 2015).

In relation to the goals defined within the document by the CIBSE the introduced tool aims to support goals A (*correct sizing of plant and network*), as well as E (*optimising the use of low carbon heat sources to supply the network*) up until stage 3 (*Design*).

The customer's input in stage 1 is taken as input to the software, so the tool is supposed to help solely the developer/owner as well as the designer. Information obtained from

performing simulations with the tool is to be handed over to the constructor as a first approximation of the basic system set-up parameters. From that detailed system design is to be performed, likely with offering a deeper level of detail tool like NetSim. The feasibility stage is to be supported by the integration of investment cost approximation for the most investment intensive parts off the system.

The motivation to work on a piece of software like that came from the lack of publicly available options to use for a previous project on the development of a small-scale HP driven DH network.

Also, from practical experience in the field of DC it was experienced how time consuming first assessments before actual planning are. Hence, it is expected that the software prevents designers from spending effort and time on a project before knowing if the project is feasible at all. This in fact makes the software a decision-making tool, that might be of interest for industry at a potential further stage of development.

1.3. Objectives

The tool is supposed to be built in a modular form, which means it can be extended to offer more options and functionality later on. It is planned that the tool expects user input, describing the basic grid topology, load distribution along the network and general system parameters. From those inputs a piping system is designed with an investment cost approximation of the pipework. Further the sizing of circulation pumps, HPs and thermal storage shall be performed. Approximate investment costs for HPs, circulation pumps and storage are to be generated as well.

The aim is to realise these calculations for HP driven systems with constant flow temperature throughout a year. It is planned that the tool designs systems as stand-alone systems without the need of integrating back-up heat sources. The decision of including a back-up system, mostly fossil fuel powered, is to be made independently from the tool and hence is out of scope. The thermal store shall be sized to support the HP system in a way that it can facilitate all heating or cooling load reliably over the whole year (Wiltshire et al., 2014).

Based on a user-set expected flow temperature an approximated value of electricity usage of the heat supply system over a year is to be calculated. This will be based on an average seasonal coefficient of performance (COP) of water-source HPs. At this first

stage of development systems designed will be confined to water-source HP supplied systems to test functionality of the algorithm.

By changing parameters and rerunning multiple simulations the user is to be enabled to quickly compare different possible system configurations.

In terms of system design, it is decided that the tool is confined to the supplier's side. Meaning design of individual customer connections is not taken into consideration. Moreover, operational cost of the system as well as detailed control mechanisms are not examined on. Those areas are depending on several different factors, outside of the scope of the issues that are planned to be addressed by the introduction of the tool.

To keep the input parameters simple the tool aims to limit economic considerations to initial investment costs of the elements designed.

1.4. Approach taken

The approach taken to reach the defined aims and objectives is represented in Figure 4.

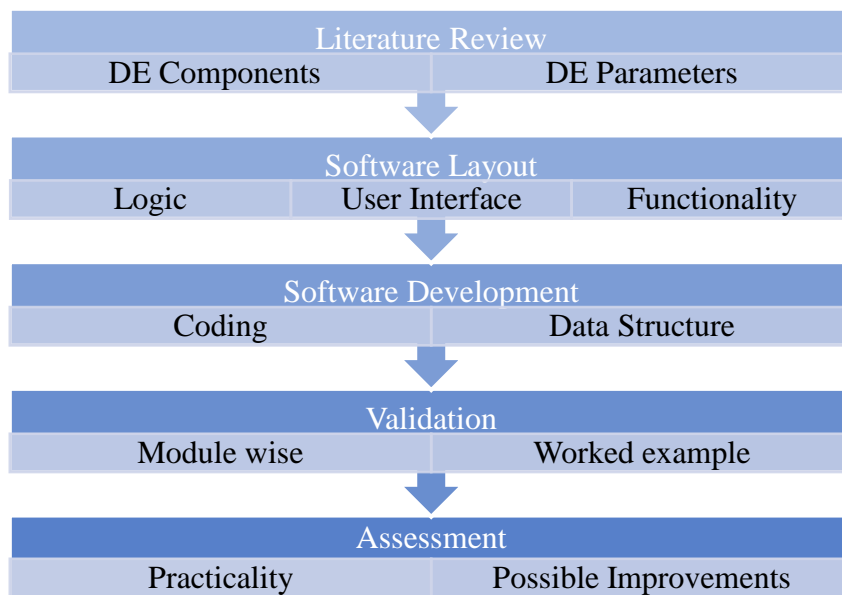


Figure 4: Process of tool development (own depiction)

Before starting to work on the tool itself an overview of available technologies, standards and system parameters is given. This is necessary to have the software running based on established engineering principles.

The literature review mainly focuses on two areas, DE Components and DE operational parameters. This part of the process is explained in section 2. Additionally, an outline of the current state of the art of DE within Europe and especially the UK, along with applied simulation models is being presented in this section.

After considering desired outputs of the simulation tool the software layout is planned. From the knowledge gathered during the literature review options for realising the project are deliberated on. This includes the logic behind the user interface, the user interface design and general functionality of the software. The determined software layout along with the actual solution is discussed within section 3.

Every module of the tool is validated against reference values from literature, to ensure reliable results are generated. The process of this validation step is examined in the same section as well.

A second step of validation is the execution of a full worked example project to check results for soundness. Hereby also the process of running a simulation with all necessary inputs, exhibiting the efficiency of the tool, is explained. The example project is described in section 4, which is closely linked to a concluding result discussion section.

In section 5: Conclusion and further work it is reflected upon practicality of the software and possible improvements to the software in order to make results more reliable.

2. Literature review

2.1. District Energy in Europe and the UK

As discussed in section 1.1 the heating sector is a major contributor to GHG emissions in Europe. In the UK the heating sector is even responsible for almost half of the energy consumed (Foster et al., 2016). As defined in the *Carbon Plan* the goal is to reduce this number to near zero by 2050. This can be reached by reducing the demand, as well as decarbonising the energy supply. One of the proposed solutions to improve the supply side is the electrification of heating systems, while at the same time decarbonising the electricity grid (HM Government, 2011).

One of the technologies that can easily be implemented in current infrastructure is district heating schemes. This technology can supply the two main consumption categories within the residential sector, namely space heating and water heating.

The UK has a large potential for the implementation of DH schemes, as currently only 2% of the heat for building stock is provided by heat networks. The UK Department of Energy and Climate Change (DECC) states that 20% of heat supply may be supplied by heat networks by 2030 (Wiltshire et al., 2014). On a European scale it is prognosed that up to 50 % of heat could potentially be supplied by DH by 2050, with 30% in 2030 respectively (Connolly et al., 2012).

DC is not as big of a topic in the UK as DH but looking at the buildout of DC drids for example in Stockholm this might change within the next years.

2.2. District Energy network benefits

In general DE network has several advantages in comparison to decentral heat production. The major benefits are:

- *Long-term security of supply*
- *Environmental benefits*
- *Affordable warmth*
- *Less plant*
- *Space savings at the building level*
- *Easier maintenance*
- *Customer security and reliability of supply*

- *Increased safety*
(Wiltshire et al., 2014)

Potential environmental benefits come from the fact that low-grade heat is used in DH grids and it is easy to integrate renewable energy sources into DE systems.

By less plant it is meant that less heating power needs to be installed in comparison to decentralised heat production. This comes the connection of multiple loads, that do not have their peak load at exactly the same time the load profile is smoothed and hence the peak load of the whole system is lower than the sum of individual peak loads in the system. This is further explained in section 2.4.1 (Wiltshire et al., 2014).

As a conventional energy source combined heat and power (CHP) systems are used in many systems. In these systems instead of dumping the rejected heat from electricity production this heat is used to drive the heating network which makes the whole process more efficient (Danfoss, 2012). In the case of DC systems, the rejected process heat might be used to supply absorption chillers. Many supply source alternatives for heat/cooling generation are available on the market. (Colmenar-Santos et al., 2017).

Using HPs to power DE grids is in good alignment with the UK's target of electrifying the heating system, whilst making it more efficient than decentralised energy production (Foster et al., 2016). The biggest potential for GHG emissions reductions by HP powered systems comes from the fact that the UK along with most countries in the EU plans to decarbonise its electrical grid.

The UK's Department of Energy & Climate Change found that systems powered by HPs have a potential of reducing GHG emissions by 48-80% depending on different scenarios and system design parameters. Figure 5 gives an overview of the different scenarios examined on in *Heat Pumps in District Heating - Final report* (Foster et al., 2016).

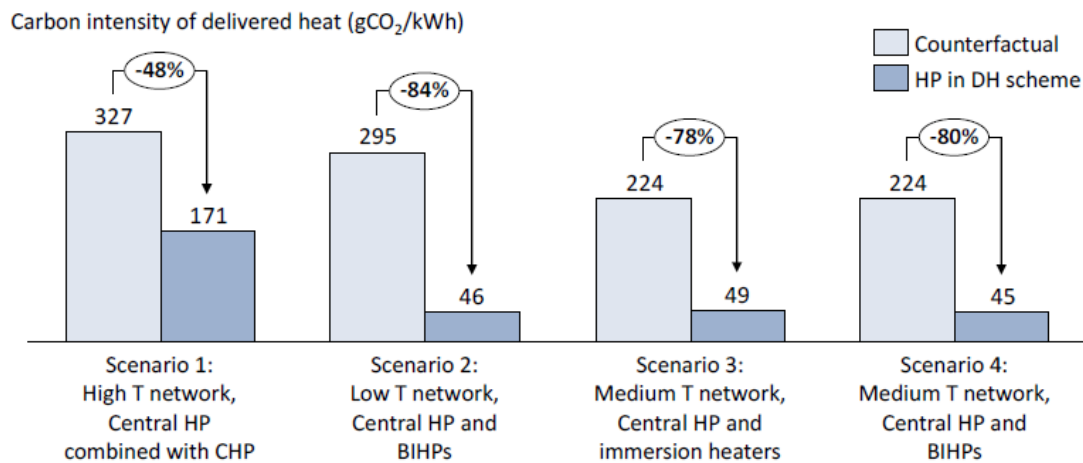


Figure 5: Comparing GHG emissions of DE with conventional systems (Foster et al., 2016).

BIHP in Figure 5 stands for Building integrated HP. The scenarios described are gas CHP powered systems for scenarios 1 and 2, and individual gas boiler powered systems in scenarios 3 and 4. The reductions would even be more significant for other fossil fuels like heating oil or coal linked to higher carbon intensity factors than natural gas. The higher reductions for systems operating at lower temperatures comes from a lower fraction of heat loss due to transmission (compare section 2.4.1).

Comparing HP heat production to direct electric heating, HPs also exhibit less GHG emissions. HPs are no renewable source by definition but operate with a specific coefficient of performance, typically well above 1 (see section 2.4.2). Assuming a COP of 3 for example and comparing that to a theoretical 100% efficiency of direct electric heating this leads to GHG emissions reduction of a third if the same electrical power source was used.

Certainly, for thermal energy produced from HPs fed from an electrical grid with a specific carbon intensity, emissions are always higher than renewable heat production (e.g. solar thermal). Nevertheless, compared to most conventional solution HPs offer a low-carbon solution especially with a low-carbon or renewable electrical power source. Another advantage of DE grids is that they may serve as thermal stores. Obviously even more in case a storage tank is included in the system. This is a gain for a future electricity grid that is exposed to fluctuations in power input due to the increasing share of renewable energy sources connected to it, supplying power at inconsistent rates. Thus, district energy grids can help in the process of grid balancing, assuming the grids are at least partly electrified (Stadler, 2008). This correlates with the aim of the project

presented within this thesis, which basically describes the design of fully electrified heat supply.

2.3. District Energy technology

Thermal energy grids offer a convenient alternative of supplying heating or cooling power to buildings in comparison to individual heating or cooling at the consumer site. The heating or cooling demand is covered by one or multiple centralised energy centres and then distributed by a heating grid to individual consumers. The fluid used for transportation in most cases is water (Wiltshire, 2016).

Grids can be operated at different temperature levels and have different types of grid structures. Another major factor to classify grids is the type of energy source used and number of heat injections into the system.

For the grid the difference between DH and DC is basically a difference in grid flow and return temperature, which leads to different pipe diameters. Additionally, those different operational temperatures lead to the need of different types of pipe insulation. Pipe insulation is not the topic of this research and hence not further discussed.

The chosen temperature depends on the consumer needs. Furthermore, the detailed set-up for sub-stations is different for both technologies, which is also not the topic of this project (Skagestad and Mildenstein, 1999).

On a high-level district energy networks are often benchmarked by two key values during the feasibility stage: Load factor and heat load (or grid) density. The load factor is defined in Eq. 1 (Wiltshire et al., 2014).

$$\text{Load factor} = \frac{\text{Annual energy consumption}}{\text{Peak demand} \times 8760 \text{ (h/a)}} \quad \text{Eq. 1: Load factor}$$

Grid density is defined as follows in Eq. 2 (Wiltshire et al., 2014).

$$\text{Grid density} = \frac{\text{Annual energy consumption}}{\text{Total length of pipeline (m)}} \quad \text{Eq. 2: Grid density}$$

In many countries amounts of subsidies are depending on those values (Skagestad and Mildenstein, 1999).

2.3.1. Temperature levels

Different DE grids can be distinguished by their operating temperatures. Typical design temperatures for DH can be found in Figure 6.

Circuit	Secondary flow temperature / °C	Secondary return temperature / °C
Radiators	Max 70	Max 40
Fan-coil units	Max 60	Max 40
Air handling unit	Max 70	Max 40
Underfloor heating	See Note 1	See Note 1
Domestic hot water service (DHWS) instantaneous heat exchanger on load	See Note 2	Max 25 for 10 °C cold feed temperature
DHWS cylinder with coil	See Note 3	Max 45 when heating up from cold at 10 °C
DHWS calorifier with external plate heat exchanger	See Note 4	Max 25 for 10 °C cold feed temperature

Note 1: Underfloor heating systems will typically operate with floor temperatures below 35 °C and typically flow temperatures of 45 °C which is advantageous for heat networks as this will result in low return temperatures.

Note 2: A minimum flow temperature of 65 °C is typical and will be determined by the required hot water delivery temperature which is typically set to 55 °C. Lower hot water delivery temperatures may be acceptable provided the volume of water is small and the *Legionella* risk can be controlled and this may allow the use of lower flow temperatures.

Note 3: Hot water storage involves a *Legionella* risk and the stored temperature is normally above 55 °C. For acceptable heat up times a minimum flow temperature of 70 °C is typical. The return temperature will generally be higher than for instantaneous heat exchangers as heat from cold rarely occurs and so higher heat losses will result.

Note 4: A central hot water calorifier would normally be designed to store water at 60 °C and with a minimum recirculation temperature of 55 °C. Typically a flow temperature of 70 °C or higher would be needed.

Figure 6: Preferred design operating temperatures for new building services systems (Woods et al., 2015).

Given temperatures are for the secondary system, meaning the consumer's side. The temperature levels at the energy centre usually need to be higher due to heat losses along transmission lines and a limited efficiency of heat exchangers. For example, heating systems with radiators typically need flow temperatures in the heating grid of around 80°C with return temperatures at 60°C. For DC these network temperature are typically in the range of 6 °C flow and 12 °C return (Woods et al., 2015).

Modern DH grids (4th Generation DH) even operate at lower temperatures. Those grids exhibit flow temperatures of below 60°C, while having lower heat losses due to the lower temperature difference against the environment. Those systems are connected to consumers that need lower operating temperatures or that heat up the supply temperature of the fluid with individual HPs (BIHPs) (Lund et al., 2014).

Temperature levels usually follow a logic linked to outdoor temperature, as heat loads mostly correlate with outdoor temperatures (Johnson, 2013). A typical operation profile for DH is displayed in Figure 7.

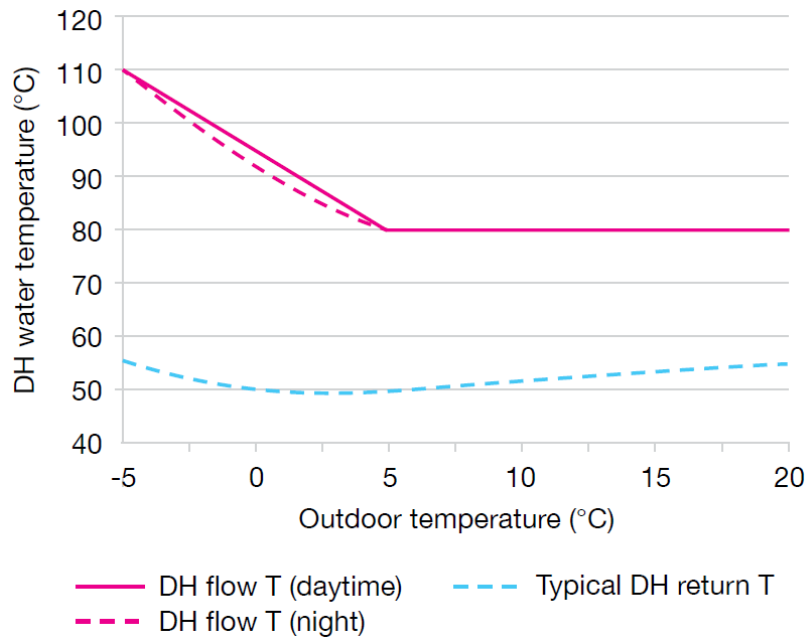


Figure 7: DH flow and return temperature variation with (Johnson, 2013).

For DC the shape of the curve would be mirrored, meaning at times of higher outdoor temperatures cooling demand is higher and hence the flow temperature usually is lower (Filipsson, 2011).

For simulations in the developed software this variation is not respected, as solely the sizing of the system and not the design of exact operational logic is of interest. Sizing is performed at peak load situations This is further explained in section 3.

2.3.2. Network sizes and types

Besides the temperature levels DE grids can be classified into different sizes. A suggestion of classification is given in the *District Heating Manual for London*. This manual classifies heating grids in three different types. The software developed is supposed to work for small scale grids, which corresponds with type 1 in the manual. This type is defined as follows:

“Type 1: Single development (small scale): Energy is generated and distributed to a single development that may include a large single building and/or a number of buildings and customers (up to around 3,000 domestic customers). The plant may or may not be owned and operated by the energy users. This would include smaller communal heating schemes. It would also include larger onsite networks with CHP generation equipment in the order of 3MWe capacity and project capital costs in the

region of £10 million. The Cranston Estate regeneration project in Hackney is a typical example.” (Johnson, 2013).

In addition to size grids can also be described by the topology of the grid. There are three basic grid distribution network types: radial, loop or mesh. Those types of grids are schematically displayed in Figure 8.

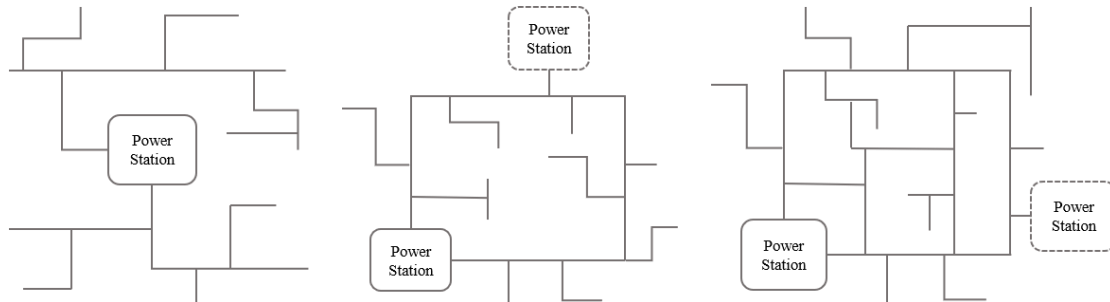


Figure 8: Network structure types; left: radial, middle: loop, right: mesh (Biedermann and Kolb, 2014).

For small and medium sized networks, the radial distribution system is mainly used. This is done because this type of grid requires the least pipework length to connect all demands, which brings investment costs down. The other two types make it easier to integrate multiple points of energy feed-in to the system and allow a more reliable supply. For small-scale systems the investment in those structures is mostly not economically feasible and also only one heat centre is used (Biedermann and Kolb, 2014). Hence, the radial system is mainly used for small-scale grids and thus networks of this type are simulated with the tool introduced within this dissertation.

2.4. Main elements of thermal energy grids

Some of the most cost-sensitive elements that at the same time require significant engineering work during the design stage are to be sized with the help of the tool described in this thesis. All elements designed within the tool are discussed in this section.

There are several more parts that need to be planned in addition to the ones discussed here to allow a flawless operation of the DE system. These include elements like expansion vessels, pressurisation pumps, water treatment plants, or electrical installations that need to be designed outside of the proposed tool and are hence not elaborated on. The design of those parts is neglected as they significantly vary depending on the chosen internal hydraulic connections and chosen system parameters.

The sizing of the above-mentioned elements might be integrated into the tool at a later stage of development.

Figure 9 shows a typical heating grid setup with the major parts included in a fully functional DH grid.

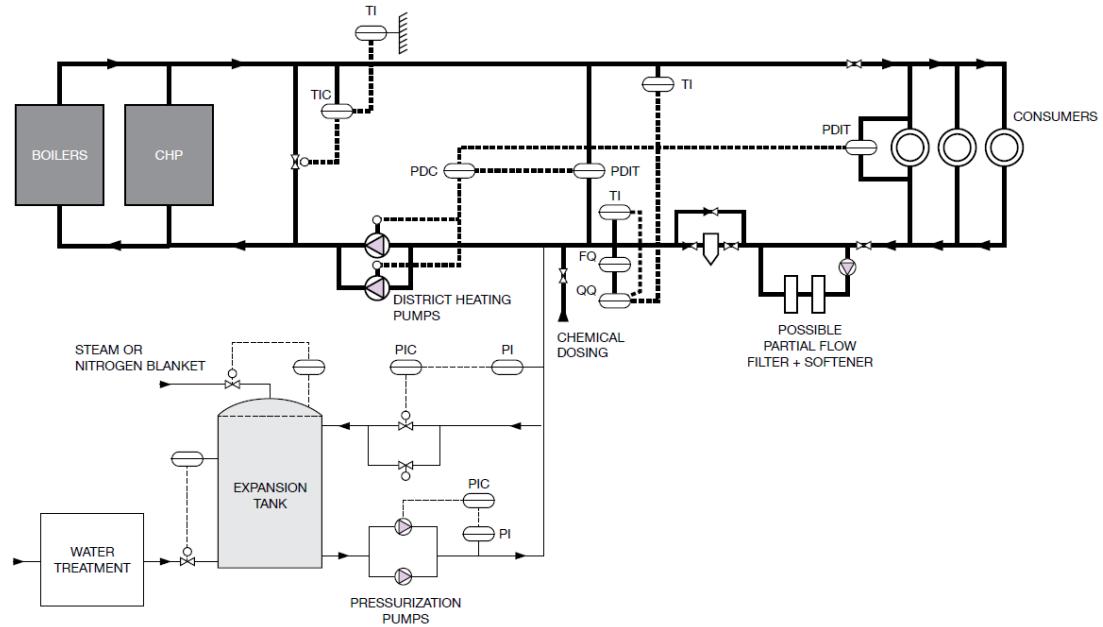


Figure 9: Typical district heat network arrangement (Johnson, 2013).

For this project the heat supply (CHP and boilers) are substituted for HPs.

2.4.1. Piping

The cost of pipework varies with the used diameter. The standard pipe dimeters chosen for the software implementation are in accordance to the EN 253 standard. Table 1 lists available pipe dimensions according to the standard for district heating steel pipes.

DN	D_o (mm)	T (mm)	D_i (mm)	Price (GBP/m)
DN20	26.9	2	22.9	600
DN25	33.7	2.3	29.1	687.5
DN32	42.4	2.6	37.2	775
DN40	48.3	2.6	43.1	862.5
DN50	60.3	2.9	54.5	950
DN65	76.1	2.9	70.3	1037.5
DN80	88.9	3.2	82.5	1125
DN100	114.3	3.6	107.1	1212.5
DN125	139.7	3.6	132.5	1300
DN150	168.3	4	160.3	1387.5
DN200	219.1	4.5	210.1	1475
DN250	273	5	263	1562.5
DN300	323.9	5.6	312.7	1650
DN350	355.6	5.6	344.4	1737.5
DN400	406.4	6.3	393.8	1825
DN450	457	6.3	444.4	1912.5
DN500	508	6.3	495.4	2000

Table 1: Pipe dimensions and pricing (Austrian Standards International, 2018).

Insulation thickness is not included in the table, as different types of insulation are used for DH and DC. To keep the software working for both cases the decision upon type of insulation is in the responsibility of the planner.

The costs per length of pipeline are extracted from *Faktenblatt - Nah-/ Fernwaerme*. In that paper price ranges in EUR for all diameters are given (Biedermann and Kolb, 2014). As prices increased over the last years values at the upper limit were chosen, linearly interpolated and converted to GBP.

For pipe dimensioning the expected heat flow is necessary to be obtain. In the case of multiple loads on a network branch annual the peak loads of every load profile are summed up. Except for dwellings, where a diversification factor is applied depending on the number of dwellings (Frederiksen and Werner, 2013). This diversification comes into play due to the assumption that not all consumers have their peak demand at the

same time, owed to individual differences in daily routine. Diversification is defined as follows in Eq. 3.

$$Diversification = \frac{P_0}{\sum_1^n P} \quad Eq. 3: Diversification$$

With P_0 being the peak load over the considered period on a respective pipe section and P the peak loads of the respective demands connected to the pipe. Rearranging Eq. 3 allows to calculate the peak load from a known diversification factor depending on the number of dwellings and their respective peak loads (Woods et al., 2015).

For the implementation of the tool described in this thesis diversification factors from the *Design Guide: Stored Hot Water Solutions in Heat Networks 2018 - Issue 1* were used (The Hot Water Association Ltd, 2018). The diversification factors are illustrated in Figure 10. Numerical values used can be found in Appendix 1.

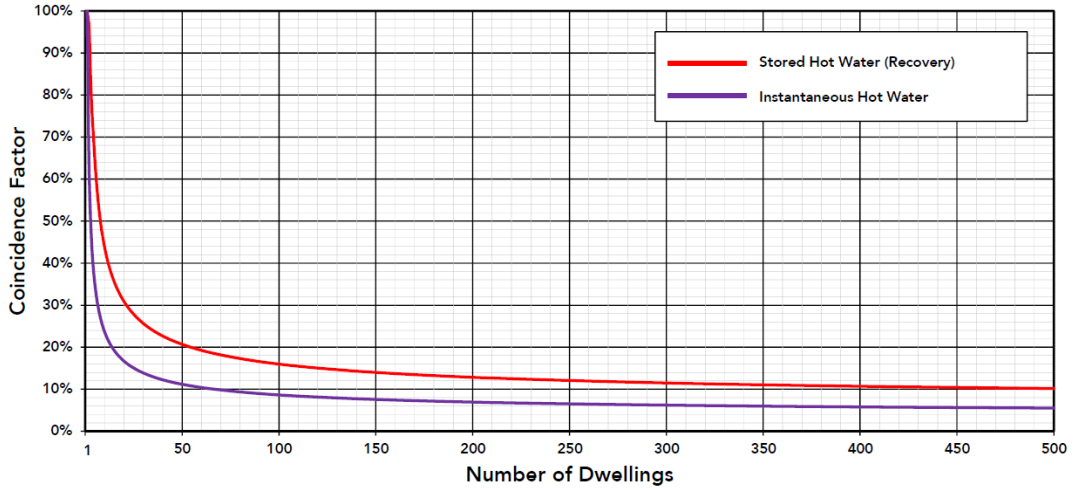


Figure 10: Hot Water Diversity (The Hot Water Association Ltd, 2018).

From the peak load occurring in a pipe section obtained as described above the maximum volume flow in this section can be calculated with Eq. 4 (Demtroeder, 2016).

$$\dot{V} = \frac{P_0}{c_p \Delta T \rho} \quad Eq. 4: Pipe volume flow$$

With a given maximum flow velocity, v_{max} it is possible to calculate a minimum inner pipe diameter, D to transport this volume flow by Eq. 5 (White and Chul, 2017).

$$D = \sqrt{\frac{4\dot{V}}{\pi v_{max}}} \quad Eq. 5: Minimum pipe diameter$$

This maximum flow velocity is typically in the range of 2 m/s for DH (Woods et al., 2015) and slightly higher for DC at around 3 m/s (Li et al., 2010). Those values however may vary from system to system and need to be set by the designer.

An additional limiting factor, in most cases even more than flow velocity is friction loss. Systems are mostly designed to only allow a maximum specific pressure drop due to friction between 50-200 Pa/m (Vesterlund and Toffolo, 2017). The *District heating manual for London* states to limit the pressure loss to 250 Pa/m for main lines and 100 Pa/m for network branches (Johnson, 2013).

To calculate the friction losses the implicit Colebrook–White equation needs to be solved to obtain the Darcy-Weisbach friction factor f .

One possible solution to do this is to apply the Swamee-Jain equation (Eq. 6), which directly yields a rather exact result for the Darcy friction factor (Ellenberger, 2010).

$$f = \frac{0.25}{\left[\log \left(\frac{\omega}{3.7D} + \frac{5.74}{Re^{0.9}} \right) \right]^2} \quad \text{Eq. 6: Darcy friction factor}$$

With ω being the surface roughness value and Re the Reynolds number (depending on flow velocity, pipe diameter as well as kinematic viscosity (ν) and density (ρ) of the fluid).

Table 2 lists recommended surface roughness values for different duct materials.

Material	Condition	ft	mm	Uncertainty, %
Steel	Sheet metal, new	0.00016	0.05	±60
	Stainless, new	0.000007	0.002	±50
	Commercial, new	0.00015	0.046	±30
	Riveted	0.01	3.0	±70
	Rusted	0.007	2.0	±50
Iron	Cast, new	0.00085	0.26	±50
	Wrought, new	0.00015	0.046	±20
	Galvanized, new	0.0005	0.15	±40
	Asphalted cast	0.0004	0.12	±50
Brass	Drawn, new	0.000007	0.002	±50
Plastic	Drawn tubing	0.000005	0.0015	±60
Glass	—	Smooth	Smooth	
Concrete	Smoothed	0.00013	0.04	±60
	Rough	0.007	2.0	±50
Rubber	Smoothed	0.000033	0.01	±60
Wood	Stave	0.0016	0.5	±40

Table 2: Recommended roughness values for commercial ducts (White and Chul, 2017).

The Darcy–Weisbach equation (Eq. 7) is used to calculate the specific friction loss from f (Brown, 2002).

$$\frac{\Delta p}{L} = \frac{f \rho}{D} v^2 \quad \text{Eq. 7: Specific friction loss}$$

Inserting Eq. 4, Eq. 6 as well as Re into Eq. 7 leads to the following equation to calculate the specific pipe friction loss (Eq. 8):

$$\frac{\Delta p}{L} = \frac{0.25 \rho v_{act}^2}{\left[\log \left(\frac{\omega}{3.7 D} + \frac{5.74}{\left(\frac{\rho v_{act} D}{\nu} \right)^{0.9}} \right) \right]^2} \cdot 2 D \quad \text{Eq. 8: Specific friction loss – implemented formula}$$

All calculations for friction losses only work in turbulent flow conditions ($Re > 2300$) (Ellenberger, 2010). Turbulent flow conditions are usually present in energy networks due to the occurring flow velocities and volume flows. This was tested for several different extreme configurations.

Pipework is the major contributor to heat losses in DE networks. Energy lost along transmission lines is depending on insulation used, the temperature gradient between the fluid in the pipes and the surroundings as well as on pipe diameters, which correlates with flow velocities (Masatin et al., 2016). The approximation used within this project to obtain the fraction of heat loss expected in grids modelled is described in section 3.3.4.

2.4.2. Heat pumps

In order to decarbonise heating supply thermal energy grids offer a convenient solution, especially if they are powered from low carbon sources. As previously mentioned, HPs are an advantageous source of energy in terms of emission reduction suitable for both heating and cooling. Even more if they are fed from renewable energy production or a low carbon electricity grid.

However, from a financial standpoint HP powered system are around 35-74% more expensive than conventional system mostly powered by fossil fuels. This can be explained by several reasons:

- *High capital cost of heat pumps (particularly MW-scale heat pumps)*
- *High electricity price compared to gas price, projected to continue over the next few decades*
- *Lost revenue from electricity sales when compared with schemes involving gas-CHP*
- *Higher capacity of heating plant required (versus gas-based district heating) where building-integrated heat pumps serve the peak demand in individual dwellings*
- *Higher network costs (versus gas-based district heating) where low temperature networks require larger diameter pipes (assuming conventional pipe materials are used)*
(Foster et al., 2016)

The use of HPs limits the range in which heating grids can be designed, as they can only reach certain flow temperatures with reasonable COP, defined as follows for heating (Eq. 9):

$$COP_{heating} = \frac{Q_H}{W_{el}} = \frac{|Q_C| + W_{el}}{W_{el}} \quad \text{Eq. 9: } COP_{heating}$$

and for cooling (Eq. 10):

$$COP_{cooling} = \frac{|Q_C|}{W_{el}} \quad \text{Eq. 10: } COP_{cooling}$$

With Q_H being the heating power, Q_C the heat taken from the warm reservoir and W_{el} the electrical power (Grassi, 2017). Which leads to the relationship between the COP of heating and cooling as defined in Eq. 11:

$$COP_{heating} = COP_{cooling} + 1 \quad \text{Eq. 11: } COP_{heating} \text{ and } COP_{cooling}$$

Depending on which side of the thermodynamic process is used, either vaporisation or condensation, the HP is operating in cooling or heating mode. So Q_C can either be the heating source or environment to be cooled.

The COP of a HP is depending on the source temperature as well as on the required supplied temperature, which in energy networks is the flow temperature of the grid. There are several different types of HPs. The different constructions are not discussed here in detail. One way of classifying HPs is the type of heat source, which significantly influences the efficiency and size of a HP. Mainly there are three different sources

available: air, water or ground source systems. Those systems transfer heat to a fluid which can be gaseous (mostly air) or liquid (mostly water). For DE systems modelled within the tool liquids are assumed to be used for distributing heat. Within this project at the current stage HPs are confined to water source HPs as lined out in section 1.3. (Grassi, 2017).

Modern water source HPs can reach COPs of around 3 for heating with rather low source temperatures (around 10°C) and high flow temperatures (90°C). These values can go up to 10 with higher source temperatures (European Heat Pump Association (EHPA), 2018).

Typically, heat sources are sized from a load duration curve resembling the annual energy demand in a sorted form. In conventional systems a low-carbon energy source is responsible to supply 40-50% of the peak load. Systems designed in that way usually supply around 85% of the annual energy demand from those low-carbon heat sources, which is defined as base load. Base load sometimes is split in base and intermediate load. The rest is covered by peak load back-up systems, mostly fossil fuel powered (Wiltshire et al., 2014). Figure 11 shows a generic load duration curve explaining the concept of base load and peak load for energy source sizing.

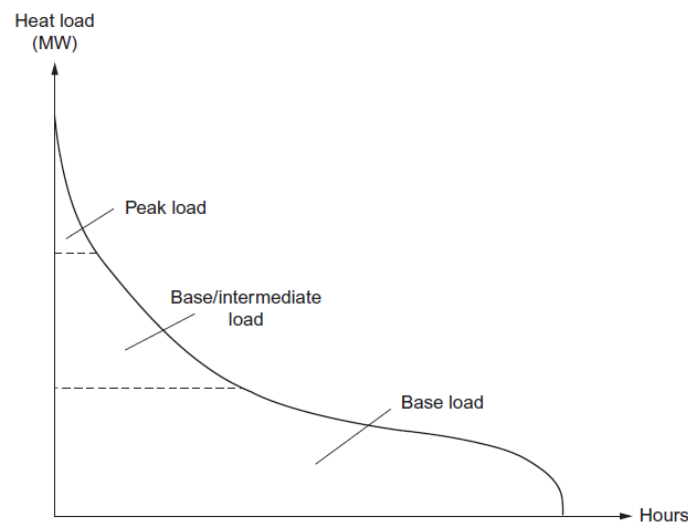


Figure 11: Typical load duration curve of annual heat consumption (Wiltshire, 2016).

The heat source, in the present case HPs in combination with a thermal storage, has to supply all demand in the grid and additionally all potential heat losses in the grid. The main reason for heat being lost is transmission losses in the grid, which can make significant amounts over a year (Masatin et al., 2016).

The pricing of HPs is approximated with the data given in *Allocation of investment costs for large-scale heat pumps supplying district heating* (Pieper et al., 2018). From the data average cost per kW thermal HP power is extracted and from that the approximate investment cost for the HP is calculated. The investment cost evaluated per kW of thermal power for water source HPs are GBP 1,387.67.

Often times the supply is split between multiple HPs, to avoid the machines from running in low partial load (Grassi, 2017). This also brings the benefit that in case of failure of one HP the system might still be able to operate with support of a storage tank.

2.4.3. Thermal energy store

Thermal energy stores, either for cooling or heating, are used to balance energy demand and supply. This can be done for different time frames, depending on the system design. Energy can be stored to support fluctuations from a daily or hourly up to a seasonal basis.

The application discussed in this paper is a solution to support seasonal fluctuations. As systems designed with the software tool are meant to drive a heating grid without the integration of heat sources in addition to the HPs, the store needs to take over the function of the peak load source in comparison to a conventional system (Wiltshire, 2016).

This means that for the systems described here all annual energy needs to be produced by the HPs and the thermal store solely shifts overproduction to times where more thermal power than the HPs can supply is needed in the grid at a specific time. In case the annual HP production is below consumption a back-up system is necessary or the HPs have to be sized bigger.

Assuming the heating grid is connected to an electricity grid supplied by renewable energy sources the thermal store can also act as an electric grid balancing element in times of peak electricity production (Stadler, 2008).

Basically, three types of thermal energy stores can be distinguished:

- Sensible heat storage
- Latent heat storage using phase change materials
- Thermo-chemical storage

The cost for thermal stores designed within the tool are calculated for sensible heat stores, resembling the simplest and cheapest of the three options. One drawback of those systems is the necessity of comparably large volumes. Cost for thermal stores implemented in the model are taken from *Thermal Energy Storage*, by the energy Technology System Analysis Programme (ETSAP) and the international Renewable Energy Agency (IRENA). The value used for pricing is GBP 5.00 per kWh of thermal capacity.

It is considered that sensible heat stores are typically around 10% oversized owed to a mixing zone that is limiting the usable volume (Woods et al., 2015).

Factors relevant for designing thermal stores are capacity, power, efficiency, storage period, charge and discharge time. Capacity is the amount of energy that can be stored, power in this context is defined as how fast the store can be (dis)charged, efficiency respects heat losses from charging and discharging, charge and discharge time is the time necessary to fill or empty the whole store (IRENA and ETSAP, 2013).

Figure 12 displays a possible solution of connecting a thermal store to the grid.

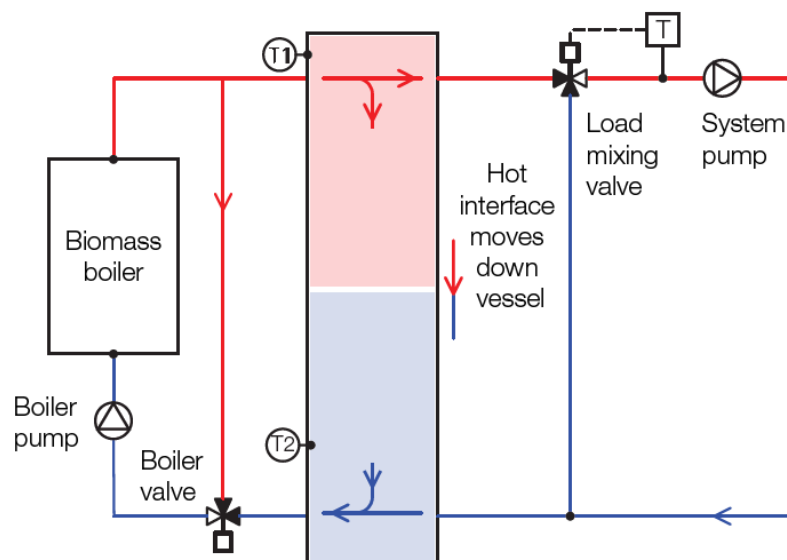


Figure 12: Schematic of a possible arrangement of a thermal store (Woods et al., 2015).

In the displayed type of connection, the thermal store also takes over the function of a hydraulic separator. The store is loaded by a separate storage pump. Again, in the described project the heat supply (in this case a biomass boiler) is realised with a HP system. This scheme in combination with the scheme shown in Figure 9 (section 2.3) represents one of many possible hydraulic connection solution of a system designed

with the proposed software. The specific hydraulic set-up needs to be defined by the planner.

2.4.4. Network circulation pumps

As described in sections 2.3 and 2.4.3 three major types of pumps are typically installed in district energy grids.

- Source pumps
- Pressurisation pumps
- Network circulation pumps

The source pumps transport water between the heat source and the thermal energy store. The pressurisation pump system in combination with the expansion tank is responsible for balancing fluctuations in fluid volume due to temperature differences over the year and to avoid vaporisation in the system at any time (Wiltshire, 2016). The sizing of those two pump entities is very much depending on the hydraulic set-up and is hence not calculated with the software.

Network circulation pumps are needed to circulate the fluid used for heat transport from the energy centre to the demands and back. The hydraulic head they must overcome consists of three major components:

- Pipe friction loss to the worst demand
- Pressure drop at a heat interface unit (HIU)
- Over-pressurisation of the system

Assuming all demands are connected in parallel to the network, the “worst” demand is defined as the demand with the highest pipe friction loss from energy centre to the demand’s heat exchanger and back. This pipe friction value is dictating the pump size. In addition to the pressure drop from pipe friction the pressure drop at the substation is relevant, as well as a lowest obtainable differential pressure at every substation of the system to allow flawless functionality at any time. (Danfoss, 2012).

For the developed tool it is assumed that a closed system with standard heat interface units (HIU) at the respective demands are installed. HIUs exhibit a maximum pressure drop of around 60 kPa (incl. all hydraulic installations), while the over-pressurisation is usually set to a value of approximately 100 kPa (Johnson, 2013).

Nowadays, variable speed pumps are used for district energy grids. The load is usually split between several pumps to accommodate different pump requirements throughout the year. Additionally, most of the time duty and standby pumps are installed to run the system reliably (Woods et al., 2015).

The hydraulic power of a pump, P_{hydr} can be calculated with the help of Eq. 12 (Gülich, 2014).

$$P_{hydr} = \frac{\rho g H \dot{V}}{\eta} \quad \text{Eq. 12: Hydraulic pump power}$$

With η being the efficiency of the pump, g the gravitational acceleration and the dynamic head, H .

Generally, the dynamic head is depending on pressure differences above suction and discharge liquid levels, difference between maximum and minimum geodetic suction head, as well as speed differences at suction and discharge side. As district heating grids are closed systems in most cases all those values are equal to zero and hence the dynamic head it solely depending on the pressure losses (Δp_l) in the system as described above (pipe friction, HIU pressure drop, over-pressurisation).

The hydraulic head can be calculated with Eq. 13 (Gülich, 2014).

$$H = \frac{\Delta p_l}{\rho g} \quad \text{Eq. 13: Hydraulic pump head}$$

From the necessary dynamic head in combination with the calculated hydraulic power, or the volume flow a fitting pump can be selected from a manufacturer's product portfolio.

2.5. Used base model

There are several models implemented in different simulation tools to design DE grids. One promising model for the simulation of hydraulic systems on the market and the academic field is the Todini-Pilati algorithm. This algorithm in general simplifies a grid to a system of nodes and pipes connected to each other. Figure 13 shows a n example of a simplified hydraulic network to describe the Todini-Pilati algorithm.

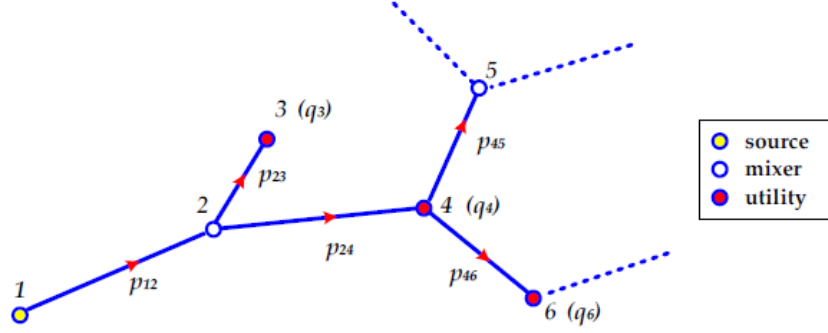


Figure 13: Schematic of a network for Todini-Pilati algorithm (Ancona et al., 2014).

The algorithm uses equations to calculate hydraulic head losses along pipes and nodes using the Darcy friction factor, described in section 2.4.1, or similar approaches.

Every node in the system is characterised by volume flow conservation defined in Eq. 14 (Ancona et al., 2014).

$$\sum \dot{V}_{IN} - \sum \dot{V}_{OUT} - \sum \dot{V}_U = 0 \quad \text{Eq. 14: Node definition}$$

With \dot{V}_{IN} defined as volume flow into the node, \dot{V}_{OUT} volume flow out of the node and \dot{V}_U volume flow extracted from the system by the node. In the system in Figure 13 mixer and utility nodes are distinguished. In mixer nodes \dot{V}_U is equal to zero, as no fluid volume is taken from the system, while in utility nodes a certain amount of fluid is taken from the system for the utility to operate properly. A utility node might for example be a direct connection to some industrial process where a part of the water is taken from the grid, used for the process and does not get fully reinjected into the grid. In the algorithm for every node and pipe a function is generated and plugged into a matrix system which then gets solved to obtain all volume flows, pipe dimensions and head losses. An example of a tool using that algorithm is EPANET, by the U.S. EPA Research.

The idea of the software designed for this thesis is very similar to the approach explained in *District heating network design and analysis*. In the project described in the paper it is tried to apply the Todini-Pilati algorithm on district heating grids (Ancona et al., 2014).

Ancona et al. validated the functionality of the Todini-Pilati algorithm against the commercial software Termis by 7-Technologies A/S and found that the algorithm is 99.8% accurate compared to results from Termis.

A simplified logic of this project is used for the implantation of the tool described in this thesis. Basically, the grid structure is adopted from the *District heating network design and analysis* paper with one major simplification of excluding utility nodes from simulations. This is done because a closed system without the need of extracting fluid from the network is assumed. From that all above described grid parameters are calculated based on conservation of mass.

3. Methodology

This section explains the chosen system for software development, the user interface, input parameters, output data and the methodology used to calculate results. Basic knowledge and formulae used in the code is lined out in section 2: Literature review.

For the implementation of the tool Python 3.7.1 by the Python Software Foundation was chosen. Python 3.7.1 was used for generating scripts, as at the time of development it was the latest version of this integrated, interactive object-oriented programming language (The Python Foundation, 2019).

Apart from the wide range of possible usage and freely available modules Python was selected because it works on most system environments and currently is the fastest growing programming language on the market. It is predicted to be the leading programming language in the next few years (Heath, 2018).

For the code to be fully operational the following Python modules need to be installed on the user's operating environment:

- csv
- math
- os
- sys
- locale
- shutil
- matplotlib.pyplot
- numpy

3.1. Approach

The idea of the project is to design a fairly complete thermal DE system with a handful of simple input parameters. The user must provide representative hourly demand profiles for a year in kW for every type of building expected to be supplied by the grid. Those profiles are referred to as model load or model demand profiles from now on.

In addition to those load profiles some basic physical boundaries need to be set by the user. After these input values are provided the Python file can be run and the whole DE scheme with all elements described in section 2.4 is laid out.

The target is to simulate type 1 (as defined in section 2.3.2) small-scale DE schemes. The grid structure is radial by default. The system can consist of any number of main lines, which themselves can have any number of sub-branches.

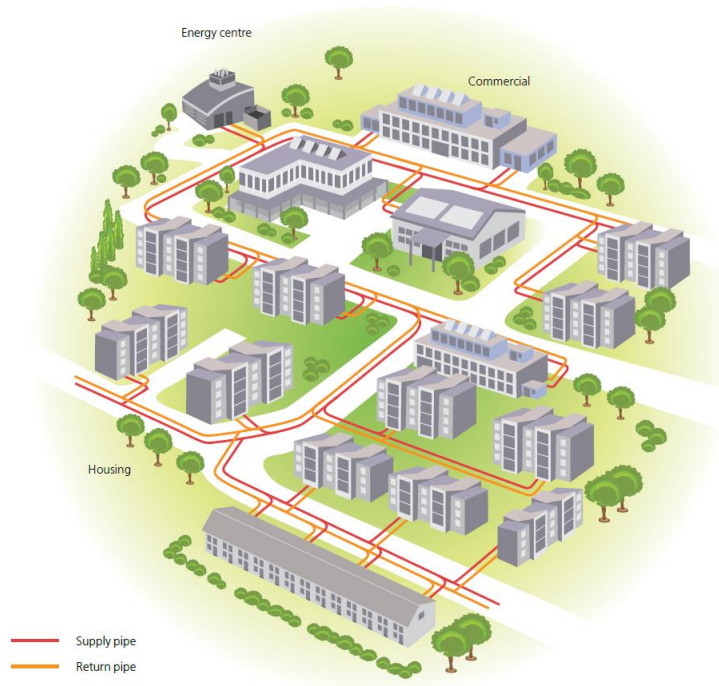


Figure 14: Representative grid structure (Wiltshire et al., 2014).

The major limitation of the tool comes from the available level of sub-branches, which is limited to one. Meaning that a sub-branch connected to a main line cannot have another sub-branch connected to it. This is done mainly to keep the interface simple and allow quicker generation of results. More levels would make the process more complex and a more extensive user interface needed to be created.

However, looking through several existing projects a wide range of projects could be simulated with that level of detail, especially DC grids that are often times even more local than DH grids (WienEnergie GmbH, 2019).

The logic implemented is based on the Todini-Pilati algorithm (see section 2.5), without the existence of utility nodes in the system. Every branch-off from main lines is defined as a mixer node, connected by pipes to other nodes. No utility nodes exist in schemes simulated, as it is assumed that the system is a closed cycle, because substations are indirectly connected. Hence, HIUs do not need to extract water from the system in order to operate properly (Skagestad and Mildenstein, 1999).

3.2. Interface and data input

The user interface at the current stage of development is command line based with no graphical user interface (GUI). All basic pre-settings for calculation are provided by the user either in form of comma-separated values (.csv) or text (.txt) files. The values

needed for generating the grid typology are obtained interactively by the software through prompted command line inputs.

The file structure of the software is set-up of a main directory containing two Python files with the actual code. The code generated to reach the defined targets is split into two scripts. One main script called “*districtenergy.py*” and one sub script “*heatpump.py*” which is imported as module into the main script. The main directory also has three sub-directories. Two for the user to supply model demand profiles and general grid parameters together with one solely for the software to save simulation results. The file structure is shown in Figure 15.

Name	Ext	Size
↑ [..]		<DIR>
📁 [basics]		<DIR>
📁 [demands]		<DIR>
📁 [results]		<DIR>
📄 districtenergy	py	30,032
📄 heatpump	py	5,800

Figure 15: File structure of the tool (own depiction).

The files with information necessary for any calculations are spread over two sub-directories:

- \basics
- \demands

The folder “*basics*” contains four files that may not be renamed and the structure not to be changed to guarantee functionality of the tool. No additional files are supposed to be added to the folder. The tool reads in those files and takes over the boundaries defined in it by the user. Therefore, values can be changed to the user’s needs depending on the desired system configuration. The files stored in the “*basics*” directory are shown in Figure 16.

Name	Ext	Size
↑ [..]		<DIR>
📄 diversification	txt	2,921
📄 pumps	csv	290
📄 basics	csv	323
📄 pipes	csv	504

Figure 16: Files within \basics (own depiction).

Three of the files are .csv files and one is a .txt file, containing the values defined below:

- *basics.csv*, containing basic values for general grid dimensioning:
 - Maximum allowed flow velocity in pipes within the grid, v_{max} [m/s]
 - Flow temperature [°C]
 - Return temperature [°C]
 - Maximum allowed specific friction losses in pipes [Pa/m]
 - Specific heat capacity, c_P [kJ/kgK]
 - Kinematic viscosity, ν [m²/s]
 - % random [float value between 0 and 1] (explained in section 3.3.4)
- *pipes.csv*, a table containing pipe standard widths and pricing. By default, it contains the values given in Table 1:
 - Standard widths (name)
 - Outer diameter [mm]
 - Wall thickness [mm]
 - Inner diameter [mm]
 - Specific prices [GBP/m]
- *pumps.csv*, containing parameters necessary for the design of the circulation pumps, further discussed in section 3.3.3
 - Gravitational acceleration [m/s²]
 - split [integer value greater or equal to 1]
 - redundancy [integer value]
 - Pressure drop at HIU [bar]
 - System over-pressurisation [bar]
- *diversification.txt*: List of diversification factors, newline delimited. By default, values are from the *Design Guide: Stored Hot Water Solutions in Heat Networks 2018 - Issue 1* (see Figure 10) for stored domestic hot water (DHW) networks are used.

The folder “*demands*” can take an arbitrary number of model demand profiles occurring in the grid. For every demand type that occurs in the grid one Python readable file with newline delimited numerical values needs to be added to the folder. Those files have to contain hourly demand values for a full year (8760). It does not matter in which unit they are given, only load distribution over a year is of importance for the calculations at that point. Profiles are being scaled to fit the annual demand. This process is further explained in section 3.3.1.

All results generated by the program are stored within the sub-directory:

- */results*

Whenever the tool runs a simulation this folder is emptied and filled with new result files during runtime. This is done to refrain the software from storing data of different simulations to the same folder. If multiple scenarios are to be compared, results of every scenario need be stored to another location before re-running the tool with different parameters.

3.3. Logic of the tool

This section is a step-by-step description of what the Python scripts are doing, with references to the theoretical background given in section 2.4.

Figure 17 describes the processes during a simulation, indicating major inputs and outputs. Every blue filled box is a process step and is described in detail in a separate sub-section of this chapter.

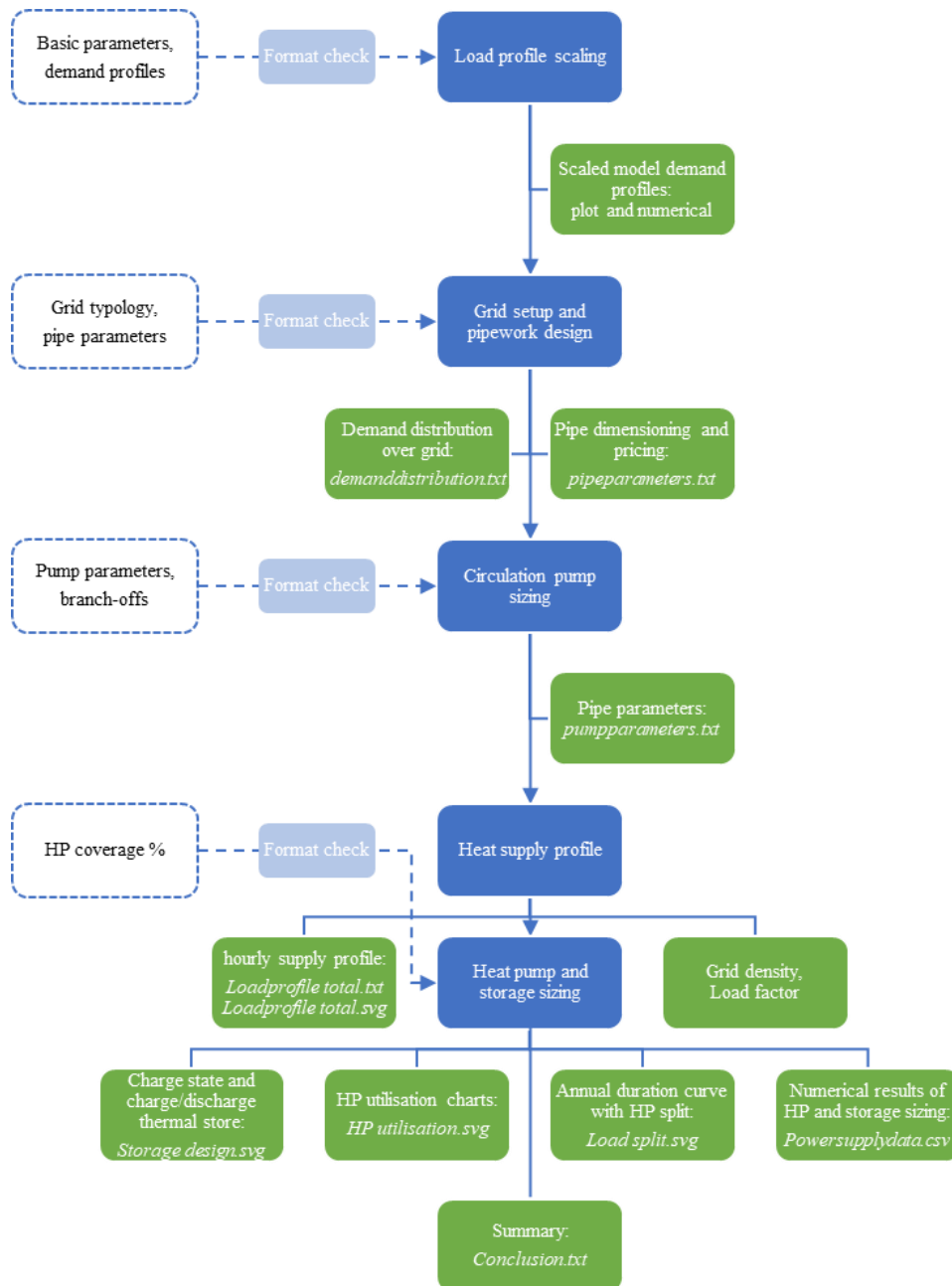


Figure 17: Simulation process overview; inputs: dashed outline; process steps: blue; outputs: green (own depiction).

The whole process starts with the program loading variables from the “basics.csv” file in order to have all general boundaries set for further calculations. Upon read-in the software checks if all values fulfil the data structure requirements. If this is not the case the program aborts and the user is presented with an error message.

After successful read-in of basic data the “results” folder is emptied to allow the software to save new results. After that the simulation actually starts.

The tool prompts the user to give several inputs on the command line. Whenever the user is asked to support information, the software automatically checks if the given values are in the expected data format for the respective parameter (integer, float, or string). Moreover, the user can abort the actual simulation at any given time by typing ‘q’.

In a first step after initial data structure checks of the files in the “basics” directory were successful the user tells the software of how many main lines the grid is comprised of to start the simulation. From structured sequential user inputs all critical grid parameters are automatically designed and graphical as well as numerical output is provided.

All calculations are based on the physical boundaries provided within the files stored in the “basics” directory, model demand profiles stored in “demands” and a network design idea of the user. The user has to have a grid map in place that will be modelled within the tool. The number of files supported by the user in “demands” at that point dictates the level of detail the simulation is run at. More profiles make the simulation more complex, while at the same time add detail to it. This along with the complexity of the piping network defines the number of inputs necessary to be given by the user during a simulation.

Examples of the different outputs along with impressions of the mode of data input are presented in section 4: Worked example.

3.3.1. Load profile scaling

Figure 18 gives an overview of the profile scaling process.

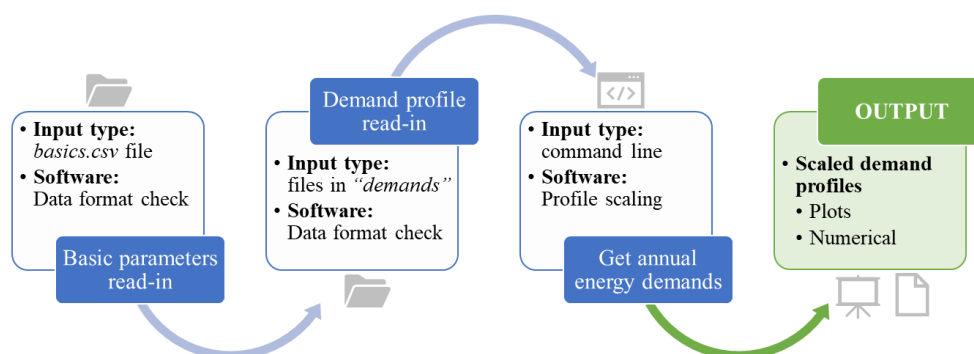


Figure 18: Illustration of the profile scaling process (own depiction).

All user-provided demand profile names are read in by the software from the “demands” folder. Throughout the simulation the demand profiles are related to by the

file names given to them, without file extension. While read-in the software checks if the files have 8760 lines and if all data types are numerical. If either of the two conditions is not fulfilled the program aborts and the user is presented with an error message indicating which file does not meet the conditions (Figure 19).

```
demands/Example.txt contains non-numerical values!  
Please check file.  
  
Program aborted.  
*****  
Stored load profile Example.txt does not contain hourly data for a year  
(exactly 8760 entries).  
Please check file.  
  
Program aborted.  
*****  
An exception has occurred, use %tb to see the full traceback.
```

Figure 19: Error messages demand profile read-in (own depiction).

The program aborts in a similar fashion if no demand distribution files are provided at all. This logic is included because all calculations are based on those model demand profiles. Hence without them no calculations can be run.

A special check is applied to the % random value, that needs to be between 0 and 1. In case this is not fulfilled the error message shown in Figure 20 is displayed and the. This value explained in section 3.3.4.

```
%random in basics/basics.csv needs to be between 0 and 1.  
Please check file.  
  
Program aborted.  
*****
```

Figure 20: Error message for % random value read-in (own depiction).

The idea is to supply as few representative load profiles as possible, while still describing the grid typology as accurate as possible. More profiles might make the simulation more accurate, but at the same time make the simulation process more complicated. As the results are to be judged as a first estimation of the initial grid properties the level of detail might be kept to a minimum.

For every available model demand profile, the user is prompted to set the annual energy demand in kWh. Additionally, the tool requests to know if the respective demand profile is a dwelling or not. This in fact defines if diversification is applied to this load type when peak loads in pipe sections are identified.

The value expected for annual energy demand needs to be either a float or integer value. When asked if the demand is a dwelling the strings 'y' or 'n' are accepted as an answer.

In case a wrong data type is typed in, the user is warned and prompted to support an acceptable value.

For every demand type the load distribution is scaled to meet the annual demand specified over a year. These scaled demand profiles are numerically stored in the “*results*” folder under the following name: “*Loadprofile [original profile name].txt*” as a text file containing hourly demand values in kW for a full year. Additionally, the scaled profiles are plotted as vector graphics and stored to the “*results*” folder named: “*Loadprofile [original profile name].svg*” at a later stage.

Model demand profiles are scaled using Eq. 15:

$$P_{i,scaled} = \frac{P_{i,model}}{\sum P_{i,model}} * Q_{annual} \quad \text{Eq. 15: Load profile scaling.}$$

All hourly loads $P_{i,model}$ of the stored load distribution are summed up. Each hourly load is then divided by this sum in order to obtain a dimensionless load distribution that sums up to 1 over a year. After that every value of the dimensionless load distribution is multiplied by the annual demand, Q_{annual} specified by the user for the respective demand type. This yields in an annual demand profile, $P_{i,scaled}$ scaled to the user-defined total annual thermal energy demand.

For every model demand profile, a Python class element containing all information provided by the user is added to a list array. The actual load profile is not stored to the class in order to save memory storage and keep the computing durations to a minimum. Element of the type demand class have a function to read their load profile from “*\results*”. Moreover, functions to find the peak load over a year in the stored profile and storing data are added to the class. A variable “*tot_num*” is initialised with 0 when creating a class element. Whenever the model demand is used in the simulation this counter is raised by one, to always keep track of how many times the model demand is used in the system.

After scaling the profiles, the software does not use the folder “*demands*” anymore.

3.3.2. Grid setup and pipework design

Figure 21 summarises the pipework design process.

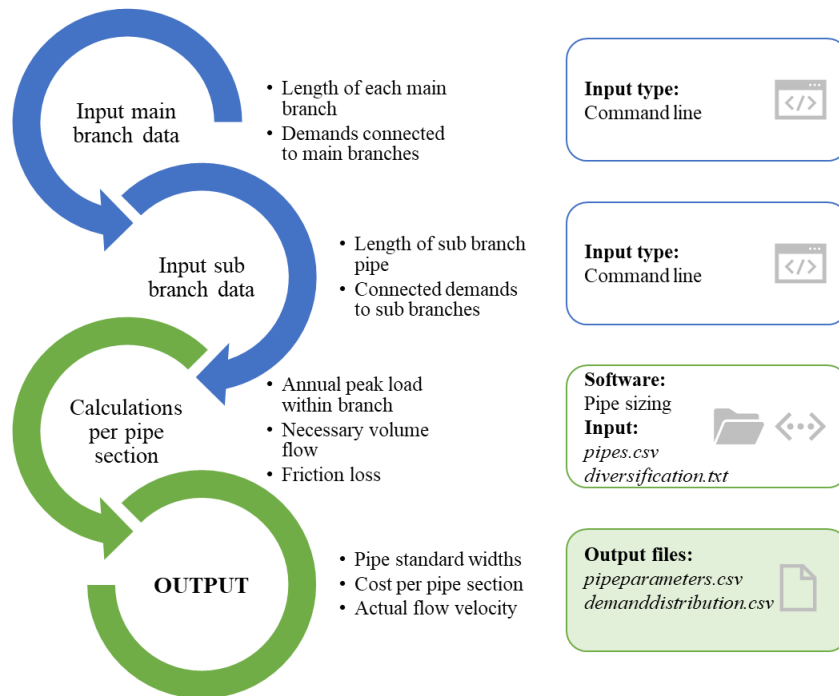


Figure 21: Illustration of the piping design process (own depiction).

The tool uses a specific logic to identify different sections of the grid. Depending on the sequence information is provided sections of the grid are named and enumerated. Figure 22 illustrates the logic after which pipes are enumerated and how branch-offs are defined in this context.

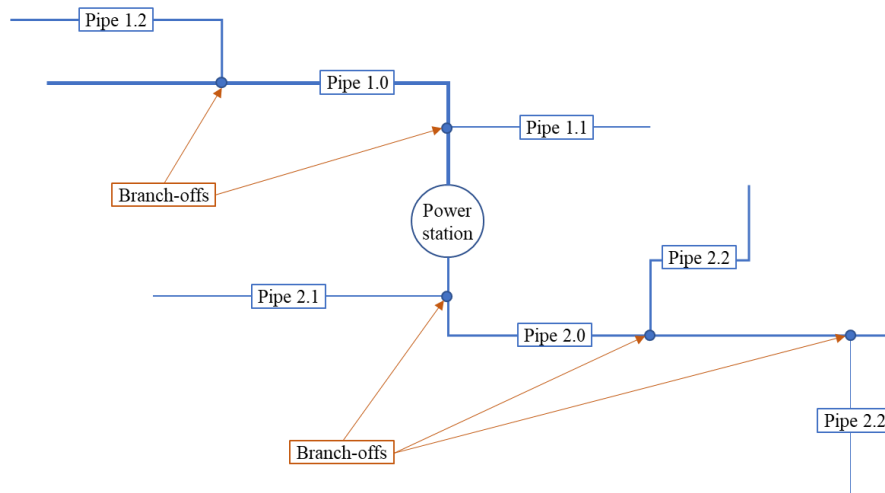


Figure 22: Type of scheme for simulation (own depiction).

All pipe names are sequentially enumerated with two integers separated by a dot. The number in front of the dot correlates to the respective main branch. The second number runs from 0 to n, with n being the number of subbranch within a main branch and 0 indicating the main branch itself. Depending on which pipe the user defines first

numbers are given in that order. It makes sense to start with entering information for sub-branches closest to the energy centre.

Every branch-off node is automatically defined as mixer node in accordance to the Todini-Pilati algorithm explained in section 2.5. Every pipe can have any number of demands connected to it. Theoretically, the number of branches is not limited.

In the second block of the code the user is requested to describe the grid layout in accordance to the above-described logic. The calculations are based on the calculations described in section 2.4.1.

First, the number of main branches within the system is typed in. This value must be of the type integer and greater than 1, as a system consisting of no pipes can evidently not be modelled.

After the user has specified the number of main branches the software loops through all main branches. For every main branch the user must provide the following information:

- Number of sub-branches connected to main branch
- Length of main branch
- Number of every model demand load connected to main branch

Once those data are provided the user is prompted to assign loads and pipework length to each sub-branch connected to the respective main branch. How many different types of demands can be added to a pipe depends on the number of model load profiles stored in the “*demands*” folder. For every pipe section the user must provide the number of each model demand connected to the section.

All pipe lengths entered by the user or presented upon output are considered trench length, which means the actual pipe length is twice as long.

Once the user has supported information for all network sections the internal calculations for grid dimensioning start.

For every model demand type the annual thermal peak power demand is determined by using the class function implemented. From that the peak power demand in each pipe section is determined by multiplying every peak power demand by the number of times the demand type occurs on the respective section. For demands defined as dwelling a diversification factor depending on the number of dwellings is applied. In case multiple dwelling model types are provided, the diversification factor is depending on the total number of dwellings connected to the pipe section, not on every individual model

demand classified as dwelling. Finally, those peak demands from individual demand types are summed up to receive a total peak power demand for each pipe section. For the peak load along main branches all demands, including the ones connected to subbranches of the respective main branch are considered.

As described in the literature review section pipe dimension are calculated from peak loads along pipe sections. From the peak load along a pipe a necessary volume flow to accommodate that heat flow can be determined (Eq. 4). This volume flow is depending on the flow temperature, return temperature of the network and fluid properties (density and specific heat capacity) defined by the user in the “*basics.csv*” file.

Based on the provided maximum flow velocity, defined in “*basics.csv*” a minimum inner pipe diameter, D is calculated by employing Eq. 5. For the obtained minimum pipe diameter the next biggest standard width is selected from the table provided in “*pipes.csv*” (format of the table must be the same as shown in Table 1).

After that for every available standard width in “*pipes.csv*” the specific pipe friction and actual flow velocity are calculated based on the necessary volume flow until the friction loss is below the user specified maximum. This leads to two minimum pipe sizes, which might differ depending on defined maximum flow velocity and allowed friction loss in the network. Whichever of the two is bigger is selected for the pipe section.

Every pipe section is stored as a Python class element. All pipe instances generated in that manner are added to two different lists depending on whether they are main lines or sub-branches.

The software might fail to yield results if the heat flow is too high to be carried by any of the pipe sizes in “*pipes.csv*” with the limitations determined by maximum flow velocity and maximum friction loss.

The process finally writes two output files to the “*results*” directory: “*pipeparameters.txt*” and “*demanddistribution.txt*”. The pipe parameters file contains the following data for every pipe in the system:

- Chosen standard width
- Pipe length [m]
- Maximum thermal power [kW]
- Maximum volume flow [m³/h]

- Maximum flow velocity [m/s]
- Maximum specific pipe friction loss [Pa/m]
- Price [GBP]

as well as total price of the whole pipework in GBP.

The demand distribution file is a summary of demands connected to every pipe section, as well as total numbers of each demand type in the whole network and annual demands for every model demand type.

As piping dimensions for DE grids are based on peak loads over the year no grid temperature fluctuations over the year are considered. It is assumed that the time of peak loads occurring coincides with the maximum temperature drop in the grid over the year.

Validation

To validate results obtained from this part of the code some test pipes were sized and compared to results published by Rehau in the technical information sheet for *Rauwitherm and Rauthermex* pre-insulated pipes (Rehau Unlimited Polymer Solutions, 2014).

For validation the roughness value was set to 0.0015 mm and physical boundaries were varied to match the conditions given in the document by Rehau. The deviations of the results were below 3% on average for different scenarios.

Additionally, friction losses in steel pipes were compared to the online pipe friction loss calculator by Grundfos. The results were also in the same range as results obtained with the tool presented in this thesis.

3.3.3. Circulation pump sizing

Figure 23 gives an overview of the pump dimensioning process.

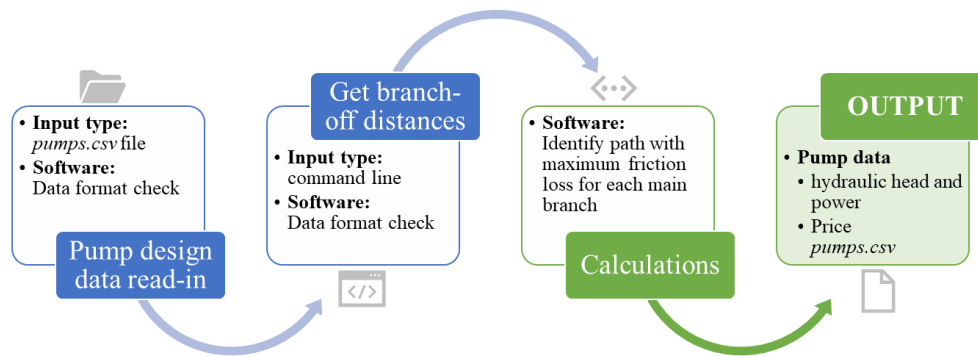


Figure 23: Illustration of the pump dimensioning process (own depiction).

Before starting simulation, the tool loads necessary basic parameters from the “*pumps.csv*” file. To make sure results are trustworthy, the user must adapt data in the file correctly.

Often the power necessary to move volume flows is split between several pumps, as described above in section 2.4.4. This feature can be defined by adopting the split value in “*pumps.csv*”. This value is an arbitrary number of pumps that share the load.

Additionally, the user can define redundancy. This value is any number of pumps in addition to the pumps necessary to perform the work necessary. Redundant pumps by default have the same properties as the other pump(s). Redundancy might be introduced in order to make the system fail-safe. In the tool it most likely is done for the sake of cost calculation.

Pressure drop at HIU and system over-pressurisation can be defined by the user to fit the grid specific needs and is by default set to the values defined in the literature review section.

Like for the read-in of the “*basics.csv*” the “*pumps.csv*” file is checked if entries fulfil the data structure requirements. All values need to be of type float or integer and split needs to be greater or equal to 1. At this time in contrast to previous data type checks in case of the check not being passed the software does not abort, but lets the user edit the files and then continue the simulation. This logic is implemented to save the user from typing in all previously supported information again. The two possible error messages the user may be presented with are shown in Figure 24.

```
basics/pumps.csv contains non-numerical values!  
Verify input values and press ENTER to continue.  
-----  
split value in basics/pumps.csv needs to be >= 1.  
Verify input values and press ENTER to continue.
```

Figure 24: Error messages pump parameter read-in (own depiction).

After read-in of data from the “*pumps.csv*” file the user is prompted to state the distance of every branch-off from the energy centre. It is checked if the branch-off distance exceeds the length of the respective main line. If that condition is true, the user is forced to retype the value.

It is assumed that every single pipe is has a demand connected at its very end. Moreover, all substations in the system are connected in parallel and all have the same pressure drop, as indicated in the support file.

With those assumption the software evaluates the connection with the highest pressure drop from energy centre to last demand. This is done for every main branch. From those maximum pressure drops in every main branch the hydraulic head and hydraulic power for the pump system is calculated using the equations discussed in section 2.4.4. The hydraulic power is calculated for the user to find a fitting pump from the preferred supplier.

The maximum volume flow is given by the maximum volume flow in the respective main branch. The maximum volume flow for every individual pump is depending on the split specified by the user, as parallel connection of the pumps is assumed. If the split is 1 the maximum volume flow of the pump is equal to the maximum volume flow occurring in the main pipe, otherwise it is split equally over the number of pumps that share the load.

A summary of all pump systems is saved to the “*results*” directory. The summary file is called “*pumpparameters.txt*” and contains the following information for every main branch:

- Number of pumps [-]
- Number of pumps for redundancy [-]
- Maximum volume flow per pump [m³/h]
- Hydraulic power [W]

- Hydraulic pump head [m]
- Price per pump [GBP]

as well as total price of the whole circulation pumping system.

Prices for pumps are linearly interpolated from the Grundfos Pumps Ltd product portfolio. Fitting pumps for several different combinations of hydraulic head and volume flow were looked up. From chosen hydraulic head and volume flow the hydraulic power for every pump was evaluated using Eq. 12. Prices were plotted with a trend line against hydraulic pump power it in Microsoft Excel (Figure 25).

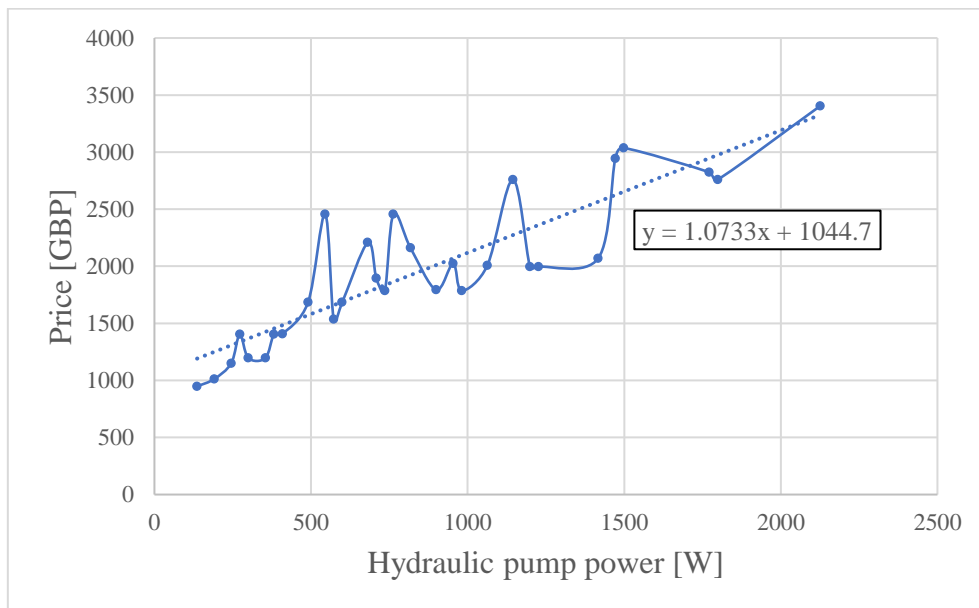


Figure 25: Price versus hydraulic pump power (own depiction, data from Grundfos Pumps Ltd).

The equation for the trendline displayed within the chart is implemented in the software to approximate prices of pumps.

Numeric data for this chart can be found in Appendix 2.

The pricing of pumps is to be understood as a rough estimation, as data from only one manufacturer were used and only for a small range of sample data. Moreover, pump prices are not solely depending on hydraulic pump power, especially for situations where one of the two parameters (volume flow or hydraulic head) is rather high or low in relation to the other.

Validation

Results for pump head are not validated at this point. Assuming the hydraulic head is calculated correctly, the hydraulic power is validated against examples executed in *Fluid mechanics* (White and Chul, 2017).

Pump heads are potentially too high as friction loss is depending on volume flow. Volume flow for its part decreases gradually along a pipe moving farther away from the energy centre as demands extract fluid and reinject it into the return line. Although, for friction loss it is assumed that volume flow is constant along the whole pipe section. More detailed calculations would need the distance of each demand connected to the grid, which would make the tool uncomfortable to use.

Hence, results from the pump dimensioning part are to be understood as rough approximations.

3.3.4. Heat supply profile

Figure 26 gives an overview of the heat supply profile generation part.

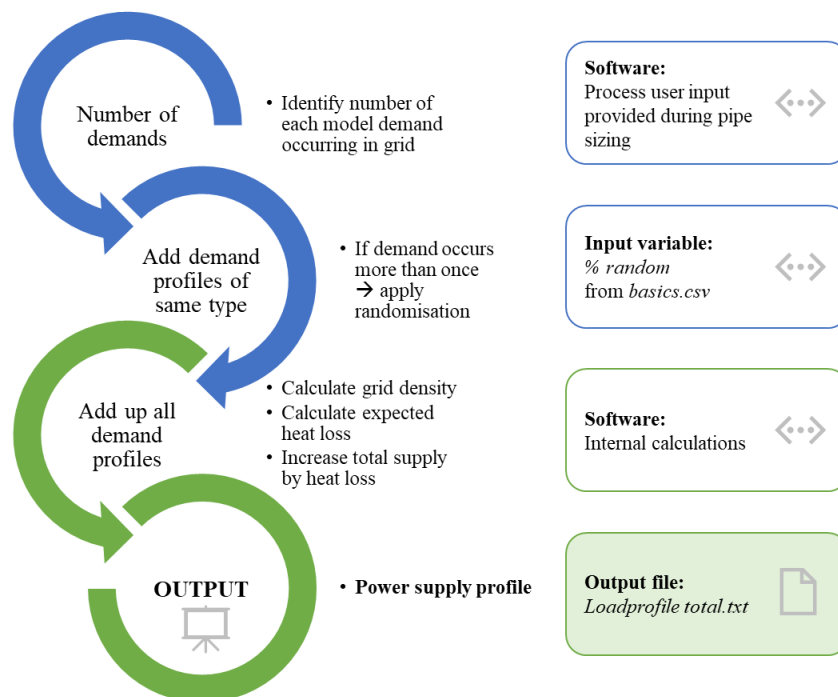


Figure 26: Illustration of the power supply profile generation (own depiction).

From all the profiles connected to the grid a total heating or cooling supply profile that needs to be accommodated by the energy centre is generated. This profile is further also needed for the design of the HP and thermal store. Those elements are calculated from this hourly load profile of the whole grid.

Simply adding up the load profiles would disregard potential diversification. Reducing dwelling profiles by a diversification factor would reduce the total annual energy consumption of the respective demand type and is hence not valid. To respect some sort of variation in the profiles that leads to shifting peak demands a logic was found to randomise profiles before summing them up on an hourly basis. The logic of randomisation implemented in the tool is described in the following:

If a model demand type only occurs once in the system (e.g. a large industry load with a very specific and predictable load profile) it is added to the total profile without randomisation applied to it. For model demands that occur more than once the profiles are summed up one-by-one. For every time the model profile is added to the total profile it is randomised.

The grade of randomisation can be varied by the user. Here the *%random* value from the “*basics.csv*” file comes into play. The % random value lies between 0 and 1. 0 means no randomisation, 1 means adding up totally random profiles. The logic has the same aim as the “Jitter” value implemented in HOMER Pro (HOMER® Energy, 2016a).

As an example, a %random value of 0.2 means that the original profile is scaled down by a factor of 0.8 and a totally random profile is added to it to contribute to 20% of the total annual energy demand. This makes sure that the total energy demand over a year stays the same, but the load distribution is changed to a certain degree. This is done before every time a model demand profile is added to the total load profile.

From this total load profile, the grid density (Eq. 2) is calculated. In accordance to the grid density an expected percentual heat loss (relative heat loss) of the grid is calculated. As an approximation of heat losses in the grid, a linear interpolation of heat loss against grid density from results presented in *Evaluation Factor for District Heating Network Heat Loss with Respect to Network Geometry* is performed (Masatin et al., 2016).

Heating grids in the article are split into three categories, depending on the quality of pipework used. Under the assumption that only grids of higher quality will be installed in future values of the better two categories were plotted with a trendline in Figure 27.

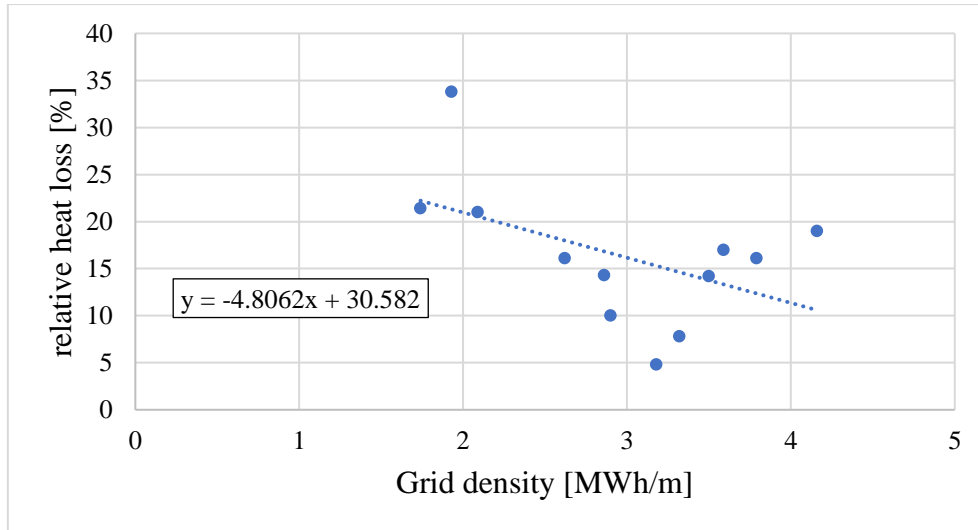


Figure 27: Relative heat loss versus on grid density (data from Masatin et al., 2016).

The equation of trendline generated in that way is used in the software to calculate the expected heat losses from transmission. This logic neglects operating temperatures as well as pipe diameters or pipe insulation used for the grid.

It is assumed that relative heat loss is constant throughout the year. With that assumption the total hourly load profile is scaled up to reflect the heat loss from transmission. Energy that is produced in the energy centre must supply all demands, as well as making up for transmission losses. Hence, the energy produced at every hour over a year is obtained employing Eq. 16.

$$Q_{supply} = \frac{Q}{(1 - \%heatloss)} \quad \text{Eq. 16: Hourly heat supply}$$

The total hourly supply profile generated by the described procedure is stored both numerical (“Loadprofile total.txt”) as well as plot (“Loadprofile total.svg”) in the “results” directory.

Validation

HOMER® Energy recommends using a “Jitter” of 0.2 for simulations in HOMER Pro. This value was tested and successfully flattens out the profile and reduces the peak demand depending on the size of the network. For bigger networks a higher randomisation might be chosen. This was not further examined.

Looking at Figure 27 reducing heat loss to be depending on grid density is not necessarily a linear function. For that reason, the R squared value is relatively low at 0.242. This indicates that this assumption is a very rough approximation.

3.3.5. Heat pump and storage sizing

Figure 28 gives an overview of the process implemented for the sizing of the HPs and thermal store.

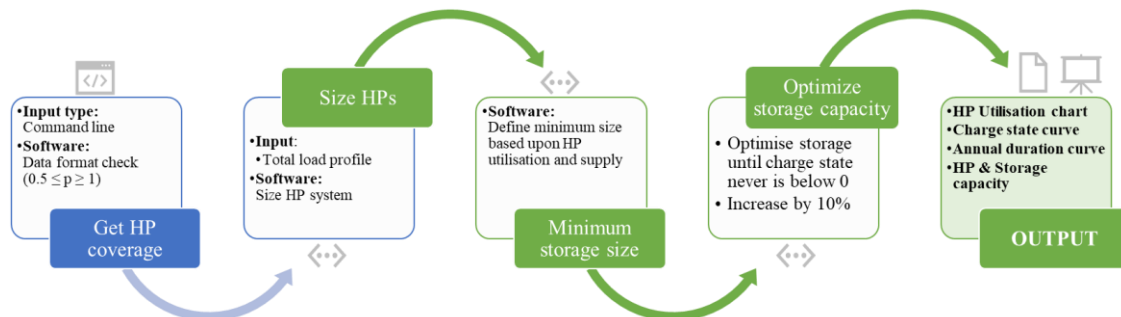


Figure 28: Illustration of HP and storage sizing process (own depiction).

Generally, the tool designs a system driven by two HPs in combination with a thermal store. The thermal store is sized to support the HPs to accomplish a fully autonomous supply throughout a full year of operation.

As discussed in section 2.4.2 conventional systems are usually powered by a low carbon source that is mostly designed based upon peak load of the network in combination with a back-up heat source. According to literature low carbon heat sources in conventional systems are capable of supplying 85% of the annual energy demand, when sized to a maximum power output of 40-50% of the annual thermal peak load (Wiltshire et al., 2014).

For systems designed with the introduced software the HP sizing is based on the percentage of demand that can be covered. To limit the storage size the default value of demand covered is set to 90%, however this value can be changed by the user. This is the only input the user has to provide for HP and storage sizing and the last of the simulation.

From the value set by the user in the command line the HP and storage sizing are initiated. The software allows values between 0.5 and 1 to be entered by the user. The maximum thermal power supplied by HPs is calculated by the quantile function within the NumPy module of Python (The SciPy community, 2018). The obtained value is then rounded to a multiple of 10 and divided by 2 in order to have the thermal power for each of the two equally sized HPs to power the system (HP1 and HP2).

In a first loop over all hours of the year an indefinitely sized storage tank with a charge state of 0 is assumed. Whenever demand is lower than the maximum thermal power of the HPs the storage level is increased by the difference between supply and demand. In case maximum supply is below demand, it is assumed this demand is covered by the store and its storage level decreased by the difference between demand and maximum supply. Storage level after every hour of the year is stored in a list. The minimum storage level is selected as storage capacity for the next step of calculation.

For the next section of code, the storage level is set to equal storage capacity (100% charge state). Again, the year is looped through hour-by-hour. Three possible situations are distinguished:

- 1) Demand is smaller than the maximum thermal power output of HP1.
- 2) Demand is between the maximum thermal power output of HP1, but smaller than the maximum thermal power output of both HPs in combination.
- 3) Demand is higher than the maximum thermal power both HPs together can supply

For situation 1) it is distinguished if the charge state of the store is below 95%. If it is HP1 runs at full capacity. It supplies the demand and with the excess production the store is charged, while HP2 charges the store at full capacity. If the charge level is above 95% HP2 shuts off and HP1 solely supplies the demand of the grid.

For situation 2) HP1 runs at full capacity to supply the grid demand. Further, it is checked if the charge state is below 100%. If so both HPs run at full capacity and the store is charged with the energy production exceeding the demand over an hour. If not HP2 is only responsible for covering the demand exceeding the capacity of HP1.

In case 3) both HPs run at full capacity to supply demand and demand that is higher than the heat output of the two HPs in combination is supplied by the thermal store. Again charge state along with HP utilisation and charge and discharge values are stored in lists on an hourly basis.

After this loop, it is checked if the discharge level is below 0 at any given time. In that case the thermal capacity is increased by the absolute amount below 0 and the loop is run through once more until charging state never reaches a value below 0 throughout a year (which is physically impossible). Otherwise the thermal capacity is kept at the same value obtained from the first iteration.

As mentioned previously, the type of storage chosen by default is sensible. This affects the pricing of the storage and brings the problem of a mixing zone in the tank with it. To make up for the mixing zone that cannot effectively be used the thermal capacity obtained is divided by 0.9 (Wiltshire et al., 2014). Charge and discharge time as well as efficiency of the thermal store are not considered within the simulation.

The logic for the storage design is inspired by two journal articles: *Hourly optimization and sizing of district heating systems considering* (Pavičević et al., 2017) as well as by *Modelling and optimization of CHP based district heating system with renewable energy production and energy storage* (Wang et al., 2015).

Output files generated from the simulations are the following:

- curves with the hourly charging state of the thermal store with periods of charge and discharge (“*Storage design.svg*”)
- HP utilisation curves (“*HP utilisation*”)
- annual duration curve with the HP split (“*Load split*”).
- All results as numerical output (“*Powersupplydata.csv*”)

Validation

One of the drawbacks from randomising the load profiles is that with every run of the simulation a slightly different result for the total load profile is obtained. To make sure that the designed grid elements are still sized correctly the model was automatically run multiple times for different grid sizes. No changes in HP sizes could be observed between runs. For storage size only slight fluctuations of below 4% resulted from the randomisation of the profiles occurred.

Various simulations were performed to validate the order of magnitude of HP systems designed by the software. Those results were compared to projects with similar size realised in Austria. Demand profiles were chosen to have similar annual energy demands and heat power plant sizes were compared. Comparison shows that HPs designed are on average smaller than heating boilers in realised projects. This may be explained by differences in load profiles used or the fact that no similar sized thermal store is installed in those projects. No definite answer can be given, as details like grid density or storage sizing are not known for the projects considered. The difference are in the range of 20% (nahwaerme.at, Energiecontracting GmbH, 2019).

3.4. Output files

All output files described up to this point can be found in the “results” directory one level below the Python scripts. In addition to those a file called “*Conclusion.txt*” is written to the “*results*” folder at the end of the simulation. This file contains the following information:

- Annual Energy demand [MWh]
- Load factor [-]
- Expected heat loss [%]
- Total pipe length [m]
- Grid density [MWh/m]
- Circulation pumps in system per main branch
 - Number
 - Hydraulic power [kW]
- Heat pumps
 - Number
 - Thermal power [kW]
- Size of thermal store [kWh]
- Price piping
- Price pumps
- Price heat pumps
- Price thermal store

4. Worked example

For the worked example an arbitrary example small scale grid is simulated, and results explained. In a real-life simulation, the user needed to identify loads and a possible grid map with the help of maps of the area where the grid is supposed to be set-up. Here a simplified grid layout is made up, including all relevant information to run simulations. In this example a heating grid is modelled. The worked example is performed for a suburban district or small town with small office buildings, some public buildings, a local hospital and two types of residential buildings.

It is distinguished between four types of buildings that are described in Table 3:

Demand name	Description	Annual heating demand
Hospital	Local hospital for a city/town. No dwelling	1,125,000 kWh/a
Office building	Office space with gross floor area of 10m ² . Resembling one workspace. No dwelling	1,500 kWh/a
Public	A larger public/communal building (e.g. school, city hall). Profile of school is used. No dwelling	700,000 kWh/a
Residential 1	Detached house with gross floor area of 150 m ² . Demand slightly higher than passive house standard. Dwelling.	3,300 kWh/a
Residential 2	Detached house with gross floor area of 75 m ² . Demand slightly higher than passive house standard. Dwelling.	1,650 kWh/a

Table 3: Worked example - Used model demands.

For the annual consumption of a hospital 45 GJ/100m³ is assumed in accordance to data published in *Energy consumption in hospitals* (CIBSE, 1999). A gross floor area of 3,000 m², with an average ceiling height of 3 m was selected to lead to a heated volume of 9,000 m³ and the heating demand stated in Table 3.

The annual demand of office building is approximated using values published in *Energy use in offices* (CIBSE, 2003). An annual energy demand of 150 kWh/m²a is selected for heating and hot water supply. The value of 10 m² per office space is chosen to reflect an average space available to one employee. So, the scaling factor for sizing the energy demand of the office buildings is the number of workspaces on a branch. This might

be done differently if the user chooses to do so. E.g. one large building as model demand profile with a larger total annual energy demand could be modelled.

For the public building an annual energy demand per year was selected in accordance to *Energy consumption analysis of school buildings in Manitoba, Canada* with 175 kWh/m²a. With an assumed gross-floor area of 4,000 m² this leads to the value stated in Table 3.

The space heating demand of the residential 1 and residential 2 model demands is selected slightly above the passive house standard (15 kWh/m²a) at 22 kWh/m²a (International Passive House Association, 2019). The two types only differ in gross floor area.

Profiles of all demands were generated with HOMER® Pro at an arbitrary annual energy demand. The location is chosen to be in Central Scotland (HOMER® Energy, 2016b). The load profiles are stored as default profiles in the “demands” directory.

It is tried to keep the example as close to a realistic set-up as possible. Hence, different branches reflect different areas within a typical grid. E.g. pipe 2.0 reflects a district with a hospital, larger housing associations and office buildings, whereas pipe 3.1 is a connected to residential area with more detached houses and a public building (e.g. school). A map of the schema used as an example is shown in Figure 29.

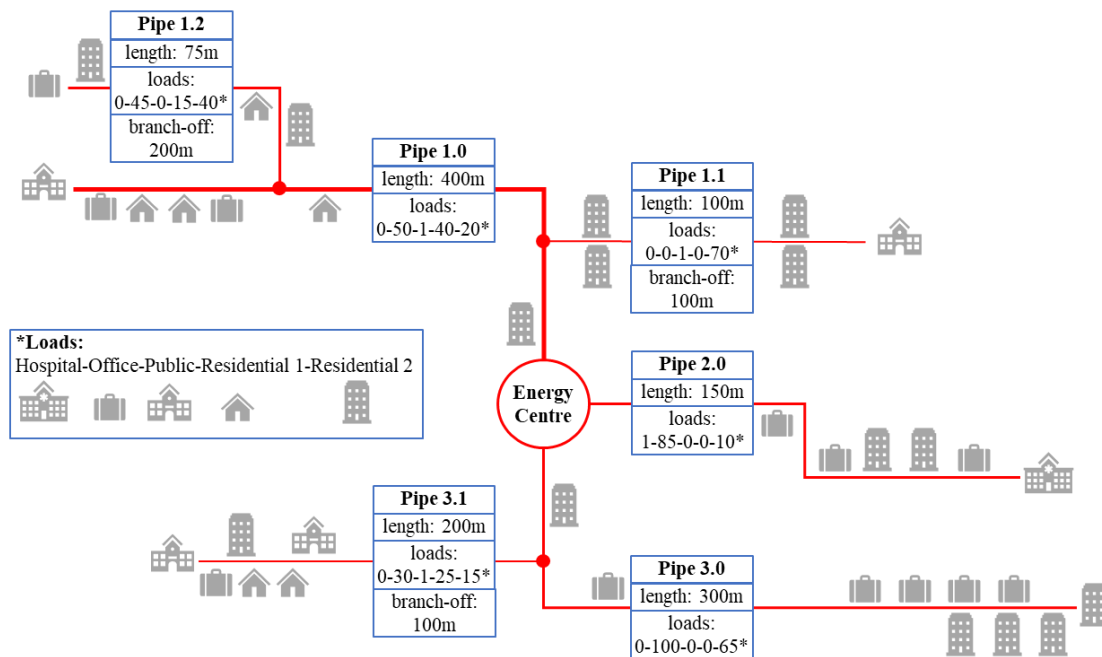


Figure 29: Worked example - Grid map (own depiction).

System boundaries supplied in “basics.csv” are listed below in Table 4.

v_{max} [m/s]	T_{flow} [°C]	T_{return} [°C]	Δp_{max} [Pa/m]	ρ [kg/m ³]	c_p [kJ/kgK]	ν [m ² /s]	ω [mm]	%random [-]
2	70	45	100	1000	4.182	$4.13 \cdot 10^{-7}$	0.04	0.2

Table 4: Worked example - Values entered in "basics.csv".

The values are chosen in accordance to guidelines defined in section 2. Fluid properties are taken from property tables for water. The UK Health and Safety Executive recommends systems to reach DHW temperatures of above 60°C in order to avoid legionella from spreading. Hence, the system flow temperature was set to 70°C to allow all consumers to reach DHW temperatures of over 60°C in their respective systems.

In the following input examples and results are discussed in the same sequence the software calculates them. Thus, the structure follows the same logic as 3.3. Numerical results on hourly basis are not included in this report due to the length of the files (8760 lines).

When running the software, the user is presented with the following information.

```

*****
Start design.
Identify demands in System. All files from folder demands/ are loaded.
Check if desired data are in folder before running simulation.

Press ENTER to start calculations or type q to quit.

```

Figure 30: Information simulation start.

4.1. Worked example - Load profile scaling

The first inputs the user has to make are stating the annual demands of the model demand profiles and specifying if they are of type dwelling or not Figure 31.


```

Please specify annual demand for each of the demand type in kWh and
identify if demand is a dwelling, meaning diversification is applied (y/n).
Enter q to quit.

Annual demand of Hospital (kWh): 1125000

Is this demand Hospital classified as dwelling (y/n): n

Annual demand of Office building (kWh): 1500

Is this demand Office building classified as dwelling (y/n): n

Annual demand of Public (kWh): 700000

Is this demand Public classified as dwelling (y/n): n

Annual demand of Residential 1 (kWh): 3300

Is this demand Residential 1 classified as dwelling (y/n): y

Annual demand of Residential 2 (kWh): 1650

Is this demand Residential 2 classified as dwelling (y/n): y

Scaled load profiles stored in \results.
*****

```

Figure 31: Worked example - Input profile scaling.

This input results in the output of scaled load profiles for every model demand profile. As an example of a load profile obtained from the simulation Figure 32 shows the profile of the model demand “Hospital”.

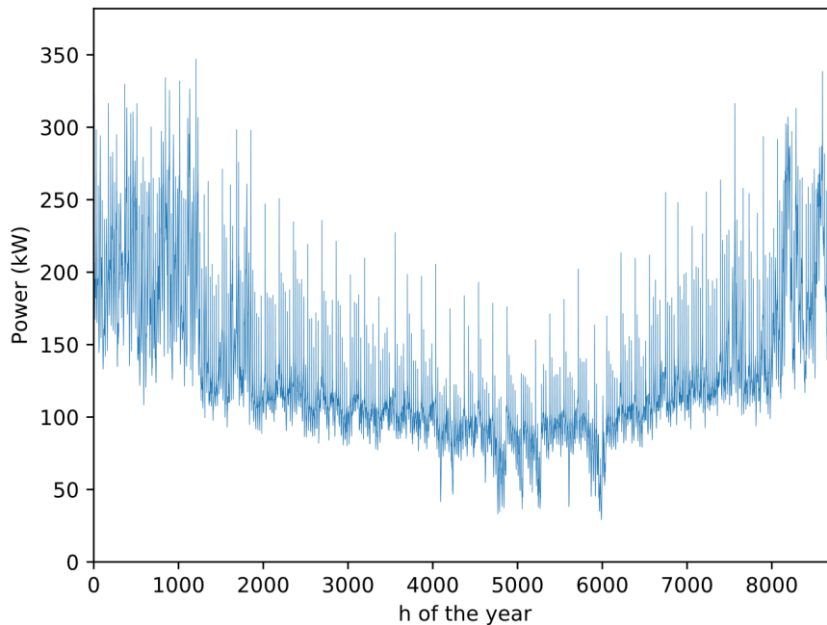


Figure 32: Worked example - Load profile "Hospital".

The diagrams of scaled profiles of the other demands can be found in Appendix 3.

4.2. Worked example - Grid setup and pipework design

The profiles scaled in the first block of the code are used for designing the grid. To perform the grid set-up data from Figure 29 are supported to the tool. Figure 33 shows

how piping data is handed over to the tool. Only inputs for “Pipe 1.0” are shown, the type of inputs is the same for any additional main lines and sub-branches.

```
*****
Please specify the basic parameters for grid design.

Number of main branches in the system: 3
-----
Design structure main branch (Pipe 1.0)

Sub branches within main branch 1: 2

Length of main branch (Pipe 1.0) (m): 400

Please state demands connected directly to main branch 1.
(neglect loads connected to eventual sub branches)

    Hospital: 0

    Office building: 50

    Public: 1

    Residential 1: 40

    Residential 2: 20
```

Figure 33: Worked example - Data input for grid design.

Once input is done for all pipe sections the tool displays the following message (Figure 34).

```
Grid design finished.
Demand distribution saved to file results/demanddistribution.txt.
*****
Pipe parameters stored in results/pipeparameters.
*****
```

Figure 34: Worked example - Pipework design and grid setup finished.

The file “demanddistribution.txt” contains the number of loads connected per pipe section , as well as a summary of demands connected to the whole grid (Figure 36). Figure 35 shows the output for Pipe 1.0 in order to exhibit the layout of the file.

```
Pipe 1.0:
Hospital           0
Office building    50
Public             1
Residential 1     40
Residential 2     20
-----
```

Figure 35: Worked example - Demand distribution along Pipe 1.0.

Figure 36 shows the conclusion output of the demand distribution, giving a summary of the demands connected to the whole network.

Total numbers:	
Hospital	1
Office building	310
Public	3
Residential 1	80
Residential 2	220
Annual Energy demands per unit:	
Hospital	1125000.0 kWh
Office building	1500.0 kWh
Public	700000.0 kWh
Residential 1	3300.0 kWh
Residential 2	1650.0 kWh

Figure 36: Worked example - Demand distribution for whole grid.

The whole content of “demanddistribution.txt” can be found in Appendix 4.

All output data of pipe sections designed for the worked example are saved to “results” as “pipeparameters.txt”. Data for Pipe 3.1 and total pipework cost of the worked example are displayed in Figure 37.

Pipe 3.1:	
Dimension:	DN100
Pipe length:	200.00 m
Max. Power:	733.71 kW
Max. volume flow:	25.26 m ³ /h
Max. flow velocity:	0.78 m/s
Max. pipe friction:	44.37 Pa/m
Price:	£242,500.00

Total price:	£1,480,937.50

Figure 37: Worked example - Output pipework design.

Results for all pipe sections are listed in Appendix 5.

4.3. Worked example – Circulation pump sizing

The file “pipes.csv” contains the same values as presented in Table 1 on page 27.

Parameters used for pump dimensioning within the discussed system are listed in Table 5. Those values are again chosen with respect to the data supported within the literature review.

g [m/s ²]	split [-]	redundancy [-]	Δp_{HIU} [bar]	$\Delta p_{overpressure}$ [bar]
9.81	2	1	0.6	0.4

Table 5: Values entered in “pumps.csv”.

To perform the circulation pump sizing the branch-off distances in accordance to the grid map need to be supported as shown in Figure 38.

```

Pump sizing.
Save desired configuration of parameters in basics/pupmps.csv.

Verify input values and press ENTER to continue.

Distance of Pipe 1.1 branch-off (m): 100
Distance of Pipe 1.2 branch-off (m): 200
Distance of Pipe 3.1 branch-off (m): 100

Pump sizing finished.
Pump parameters stored in results/pumpparameters.
*****

```

Figure 38: Worked example - Data input circulation pump sizing.

As a representative result data for the pump system in main branch 3 as well as total price of all pumps designed for the system, are shown in Figure 39.

Pump(s) main branch 3:	
Number of pumps:	3
1 pump(s) for redundancy	
Max. volume flow per pump:	15.74 m ³ /h
Hdr. Power (eff=1):	309.07 W
Pump head:	14.41 m
Price per pump:	£1,376.42

Total price:	£12,652.24

Figure 39: Worked example – Output circulation pump sizing.

The results for all three main pipes stored in “pumpparameters.txt” can be found in Appendix 6.

4.4. Worked example – Heat supply profile, heat pump and storage sizing

The thermal power supply profile does not need any user input and is calculated automatically. The user is only presented with a command line message stating that the simulation was performed (Figure 40).

```

Generating power supply profile for whole grid.
...
done.
Load profile stored in results/Loadprofile total.txt
*****

```

Figure 40: Worked example - Information supply profile calculated.

The user is presented with a plot of the thermal power supply profile (Figure 41), which is automatically stored along with a numerical value file.

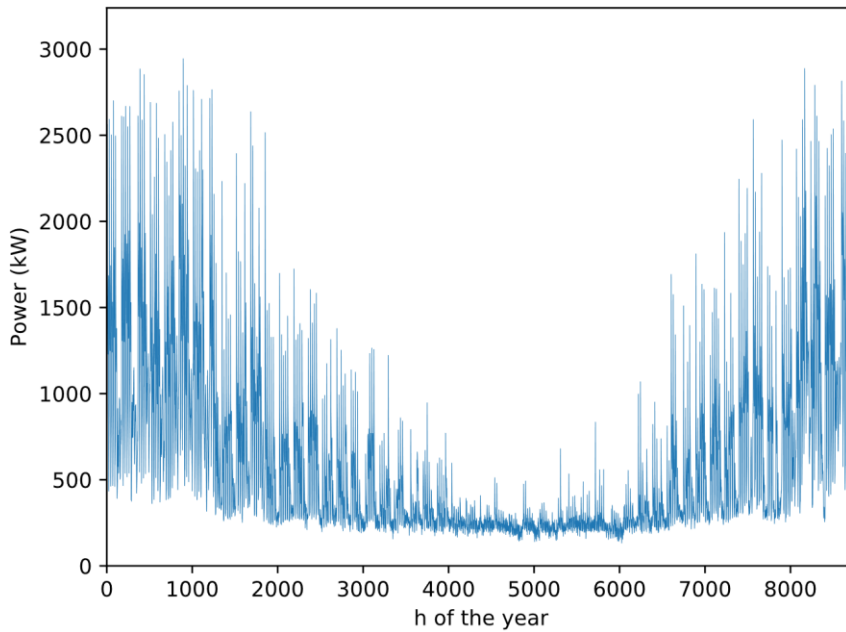


Figure 41: Worked example - Power supply profile plot.

For the simulation of the HPs and thermal storage system the default value of 90% coverage of load by HP was used. Again, this means that 90% of the annual heating or cooling demand could be covered with the HPs alone and only for 10% of the time the storage system needs to kick in to supply the heating grid. The command line input necessary for this step is shown in Figure 42.

```
Heat pump and storage sizing.

Base load percentage covered by heat pumps (standard = 0.9): 0.9

Heat pump/storage sizing finished.
To try a differnt configuration, run again? (y/n) n

HP utilisation and strage data stored in results/
Sorted annual load curve stored in results/
Summary stored in results/Conclusion.txt

Simulation finished.
*****
```

Figure 42: Worked example - Input HP and storage sizing.

The key data along with HP sizes and storage capacity can be found in the “Conclusion.txt” file. The content of the file is shown below in Figure 43.

General:	
Annual Energy demand (MWh):	4317.00
Load factor:	0.19
Expected heat loss (%):	13.64

Piping:	
Total pipe length (m):	1225.00
Grid density (MWh/m):	3.52

Circulation pumps:	
Pump(s) main branch 1:	3x 551.53 W
Pump(s) main branch 2:	3x 148.73 W
Pump(s) main branch 3:	3x 309.07 W

Heat pumps:	
	2x 615.0 kW
Given power is thermal power.	
Annual Energy supplied (MWh):	4999.11

Thermal store:	
Size (kWh):	27038.45

Price piping:	£1,480,937.50
Price pumps:	£12,652.24
Price heat pumps:	£1,706,836.61
Price thermal store:	£135,192.26

Figure 43: Worked example - Content of "Conclusion.txt"

The span in which the two HPs operate is made visible in an ordered annual load duration curve in which the HP operation ranges are filled in orange and blue (Figure 44).

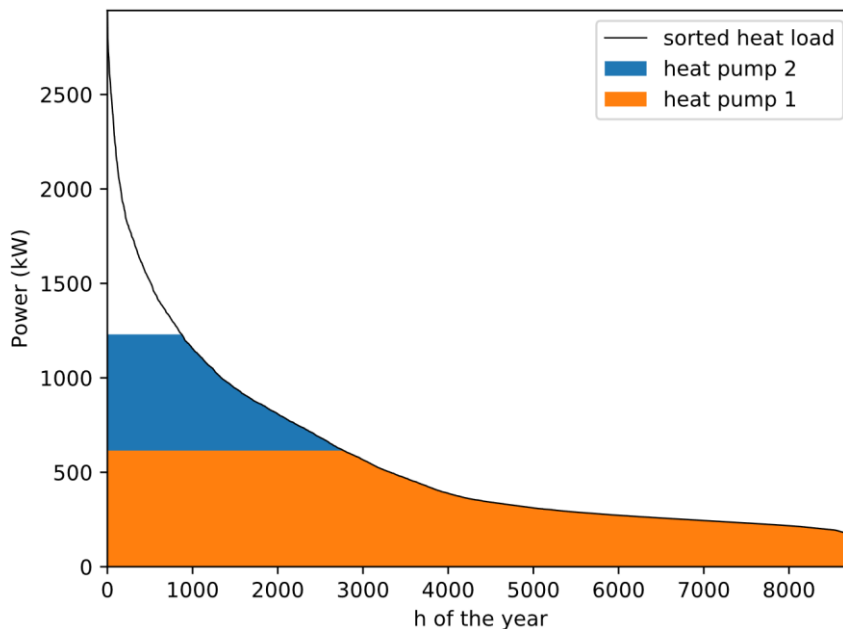


Figure 44: Worked example - Annual load duration curve with HP split.

To support the grid the operation modes of the HP are illustrated in Figure 45.

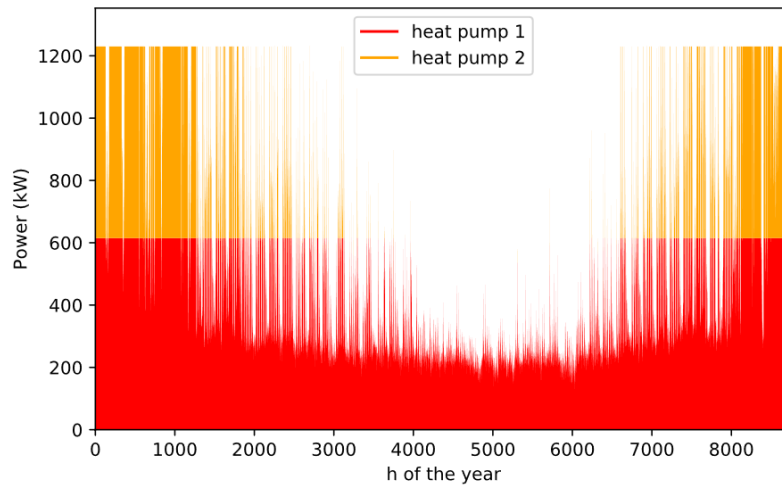


Figure 45: Worked example - HP utilisation curves.

This utilisation of the HPs leads to the following chart displaying charge and discharge times as well as a charging state throughout the year (Figure 46).

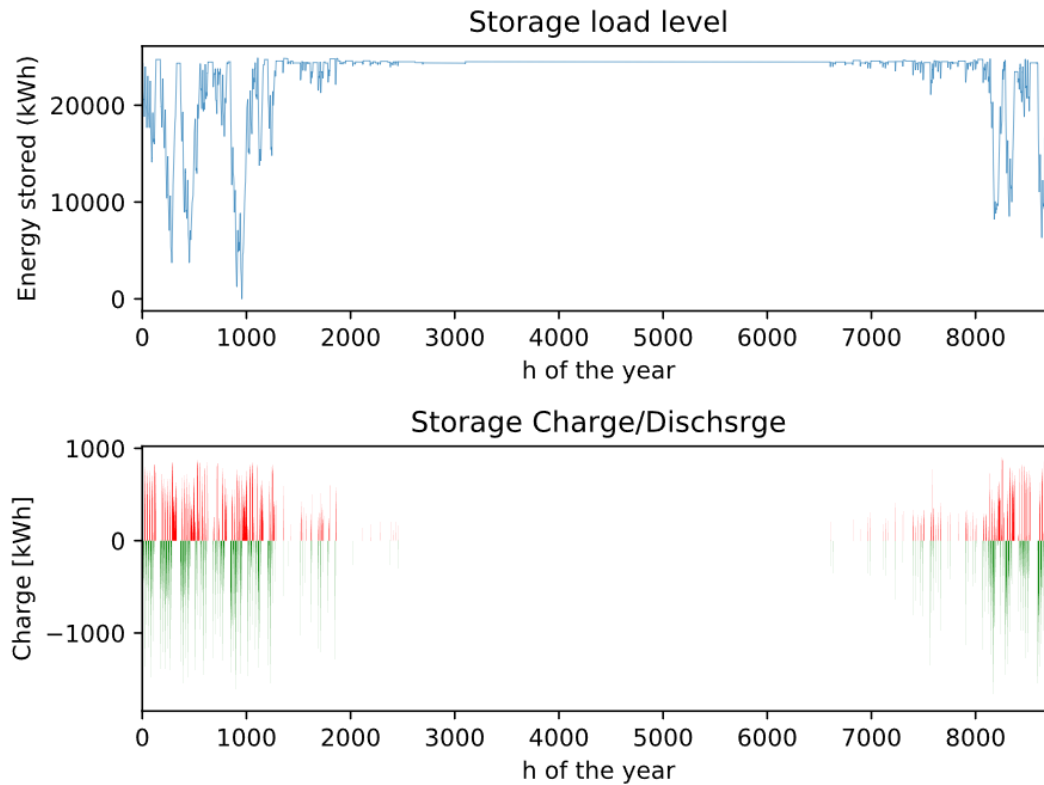


Figure 46: Worked example - Thermal store data.

All graphical outputs are automatically stored to “\results” and numerical values are stored as “Powersupplydata.csv”.

4.5. Worked example – Results discussion

The worked example performed in this thesis is done for the sake of showing the different types of inputs given to the tool as well as typical output data. Nonetheless, it is briefly discussed on the specific results in the following.

HP and pump values are not related to specific models or types of HPs. The user needs to select models from a preferred manufacturer, based on the technology implemented. Prices are to be understood as an orientation. Thus, no COPs, pump efficiencies, or electrical connection powers are calculated, as they significantly fluctuate from model to model. Moreover, large HP systems are often produced individually to the customer's needs. Another limitation in this context is that costs are estimated for water source HPs only. No other technologies are considered.

The annual energy demand in combination with the grid length exhibits a grid density of 3.52 MWh/m. This value is rather high compared to the values stated for example in *Evaluation Factor for District Heating Network Heat Loss with Respect to Network Geometry* where an average of 2.73 MWh/m is given (Masatin et al., 2016). This can be explained by the comparably short pipe lengths.

Moreover, it is obvious that the system has a strong seasonal fluctuation in demand. This might be reduced by integrating industry loads with rather constant load throughout the year. This would further improve the grid density and make a potential project more feasible.

Additionally, the software in this stage of development does not use any optimisation algorithms for system operation. In summer when demand is low, the thermal store is not used at all. It is now only used for seasonal peak loads. This is what the tool is supposed to do, but it indicates that by also using the storage system in times of low demand energy production could be shifted to times of cheap electricity in the grid. Another option would be coupling the system with renewable energy production and using the thermal store for storing potential over-production.

Further simulations with a lower HP coverage could have been run in order to potentially minimise investment costs.

5. Conclusion and further work

The tool successfully fulfils all aims except for one defined in the introduction. A simulation like the worked example used to explain the functionality of the tool can be performed within a few minutes and delivers satisfying results. The only outlined aim that was not accomplished is the annual electrical energy demand of the HP. This was neglected after it was found that performance data of different HP types are highly fluctuating with an abundance of independent factors. Covering those calculations would be in conflict to the aim of keeping the simulations as simple as possible.

With the results generated up to the current stage of development a lot of work can be taken from the first feasibility stage by automating processes. Python turned out to be a convenient programming language to generate results fast with professional output formats. Processing times on the system environment used for development and testing have been negligible.

The biggest weakness of the software is, as already mentioned the limitation in sub-branch level deepness. Technically, it would just be a small change within the code to add the option of more sub-branch levels than one, but it would make the input much more complex. For that a GUI needed to be implemented. Hence, it was decided to focus on the general functionality of the underlying logic. A GUI with the option of more detailed input might be performed later.

The current type of data input over the command line leads to another drawback. Once information is handed over to the software it cannot be amended. If the user wishes to correct input the simulation needs to be aborted and all previous inputs need to be entered again. This is another reason the interface needs to be made more user-friendly.

Functionality wise the first two blocks of load profile scaling and grid setup with pipework design are validated and deliver meaningful results. Same counts for HP and storage sizing, except for the lack of detailed operational analysis which was initially not defined as an aim. Only the circulation pump design block needs more validation.

The storage design is limited to the calculation of capacity of one type of storage. To bring this simulation closer to reality more storage parameters like charge and discharge time as well as efficiency of the thermal store needed to be considered. Furthermore, the option of selecting different types of storage system would improve this module of the tool.

For the HP system design an option to select HP type would be useful. From that a COP based on source temperature, and flow temperature could be generated, which would allow to calculate an electric load profile of the HP and the bespoke annual electrical energy demand.

This goes hand in hand with the potential to add operational details to the simulation. From more technical operational details operational costs could be determined to help performing a full economic analysis to help with an investment decision.

To conclude as soon as preliminary analysis of the system has been performed properly by the user a simulation with considerable output may be performed within a couple of minutes depending on complexity of the system. With a fitting GUI the software generated can be of great help in designing thermal DE grids in future.

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Appendices

Appendix 1. Used diversification factors

Source: Design Guide: Stored Hot Water Solutions in Heat Networks 2018 - Issue 1
(The Hot Water Association Ltd, 2018)

HWA/DG1



Stored DHW in Heat Networks - Design Guide

Table 4 - Diversification Factors for Stored Hot Water Recovery from 1 to 250 apartments

Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor
1	100.00%	51	20.51%	101	15.92%	151	13.96%	201	12.81%
2	96.01%	52	20.35%	102	15.87%	152	13.93%	202	12.80%
3	81.00%	53	20.20%	103	15.81%	153	13.90%	203	12.78%
4	71.78%	54	20.05%	104	15.76%	154	13.87%	204	12.76%
5	64.56%	55	19.91%	105	15.71%	155	13.85%	205	12.74%
6	58.07%	56	19.77%	106	15.66%	156	13.82%	206	12.72%
7	53.20%	57	19.63%	107	15.61%	157	13.79%	207	12.71%
8	49.40%	58	19.50%	108	15.56%	158	13.77%	208	12.69%
9	46.32%	59	19.37%	109	15.51%	159	13.74%	209	12.67%
10	43.78%	60	19.25%	110	15.47%	160	13.71%	210	12.65%
11	41.63%	61	19.12%	111	15.42%	161	13.69%	211	12.64%
12	39.78%	62	19.00%	112	15.37%	162	13.66%	212	12.62%
13	38.18%	63	18.89%	113	15.33%	163	13.64%	213	12.60%
14	36.77%	64	18.78%	114	15.28%	164	13.61%	214	12.59%
15	35.52%	65	18.67%	115	15.24%	165	13.58%	215	12.57%
16	34.40%	66	18.56%	116	15.19%	166	13.56%	216	12.55%
17	33.39%	67	18.45%	117	15.15%	167	13.54%	217	12.54%
18	32.48%	68	18.35%	118	15.11%	168	13.51%	218	12.52%
19	31.64%	69	18.25%	119	15.07%	169	13.49%	219	12.50%
20	30.88%	70	18.15%	120	15.02%	170	13.46%	220	12.49%
21	30.17%	71	18.06%	121	14.98%	171	13.44%	221	12.47%
22	29.52%	72	17.96%	122	14.94%	172	13.42%	222	12.46%
23	28.92%	73	17.87%	123	14.90%	173	13.39%	223	12.44%
24	28.35%	74	17.78%	124	14.86%	174	13.37%	224	12.43%
25	27.83%	75	17.70%	125	14.83%	175	13.35%	225	12.41%
26	27.33%	76	17.61%	126	14.79%	176	13.32%	226	12.39%
27	26.87%	77	17.53%	127	14.75%	177	13.30%	227	12.38%
28	26.44%	78	17.44%	128	14.71%	178	13.28%	228	12.36%
29	26.02%	79	17.36%	129	14.67%	179	13.26%	229	12.35%
30	25.64%	80	17.28%	130	14.64%	180	13.23%	230	12.33%
31	25.27%	81	17.21%	131	14.60%	181	13.21%	231	12.32%
32	24.92%	82	17.13%	132	14.57%	182	13.19%	232	12.30%
33	24.59%	83	17.06%	133	14.53%	183	13.17%	233	12.29%
34	24.27%	84	16.98%	134	14.50%	184	13.15%	234	12.28%
35	23.97%	85	16.91%	135	14.46%	185	13.13%	235	12.26%
36	23.68%	86	16.84%	136	14.43%	186	13.11%	236	12.25%
37	23.41%	87	16.77%	137	14.39%	187	13.09%	237	12.23%
38	23.15%	88	16.70%	138	14.36%	188	13.07%	238	12.22%
39	22.89%	89	16.64%	139	14.33%	189	13.05%	239	12.20%
40	22.65%	90	16.57%	140	14.30%	190	13.02%	240	12.19%
41	22.42%	91	16.51%	141	14.26%	191	13.00%	241	12.18%
42	22.20%	92	16.44%	142	14.23%	192	12.99%	242	12.16%
43	21.98%	93	16.38%	143	14.20%	193	12.97%	243	12.15%
44	21.77%	94	16.32%	144	14.17%	194	12.95%	244	12.13%
45	21.57%	95	16.26%	145	14.14%	195	12.93%	245	12.12%
46	21.38%	96	16.20%	146	14.11%	196	12.91%	246	12.11%
47	21.20%	97	16.14%	147	14.08%	197	12.89%	247	12.09%
48	21.02%	98	16.09%	148	14.05%	198	12.87%	248	12.08%
49	20.84%	99	16.03%	149	14.02%	199	12.85%	249	12.07%
50	20.67%	100	15.98%	150	13.99%	200	12.83%	250	12.05%

Note: The coincidence factors in Table 4 are based on hot water storage recovery under temperature control only.

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Table 5 - Diversification Factors for Stored Hot Water Recovery from 251 to 500 apartments

Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor	Number of Apartments	Coincidence Factor
251	12.04%	301	11.48%	351	11.04%	401	10.69%	451	10.41%
252	12.03%	302	11.47%	352	11.03%	402	10.69%	452	10.40%
253	12.02%	303	11.46%	353	11.03%	403	10.68%	453	10.40%
254	12.00%	304	11.45%	354	11.02%	404	10.67%	454	10.39%
255	11.99%	305	11.44%	355	11.01%	405	10.67%	455	10.38%
256	11.98%	306	11.43%	356	11.00%	406	10.66%	456	10.38%
257	11.97%	307	11.42%	357	11.00%	407	10.66%	457	10.37%
258	11.95%	308	11.41%	358	10.99%	408	10.65%	458	10.37%
259	11.94%	309	11.40%	359	10.98%	409	10.64%	459	10.36%
260	11.93%	310	11.39%	360	10.97%	410	10.64%	460	10.36%
261	11.92%	311	11.38%	361	10.97%	411	10.63%	461	10.35%
262	11.90%	312	11.37%	362	10.96%	412	10.63%	462	10.35%
263	11.89%	313	11.36%	363	10.95%	413	10.62%	463	10.34%
264	11.88%	314	11.35%	364	10.94%	414	10.61%	464	10.34%
265	11.87%	315	11.34%	365	10.94%	415	10.61%	465	10.33%
266	11.86%	316	11.34%	366	10.93%	416	10.60%	466	10.33%
267	11.84%	317	11.33%	367	10.92%	417	10.60%	467	10.32%
268	11.83%	318	11.32%	368	10.92%	418	10.59%	468	10.32%
269	11.82%	319	11.31%	369	10.91%	419	10.58%	469	10.31%
270	11.81%	320	11.30%	370	10.90%	420	10.58%	470	10.31%
271	11.80%	321	11.29%	371	10.89%	421	10.57%	471	10.30%
272	11.79%	322	11.28%	372	10.89%	422	10.57%	472	10.30%
273	11.77%	323	11.27%	373	10.88%	423	10.56%	473	10.29%
274	11.76%	324	11.26%	374	10.87%	424	10.55%	474	10.29%
275	11.75%	325	11.26%	375	10.87%	425	10.55%	475	10.28%
276	11.74%	326	11.25%	376	10.86%	426	10.54%	476	10.28%
277	11.73%	327	11.24%	377	10.85%	427	10.54%	477	10.27%
278	11.72%	328	11.23%	378	10.84%	428	10.53%	478	10.27%
279	11.71%	329	11.22%	379	10.84%	429	10.53%	479	10.27%
280	11.70%	330	11.21%	380	10.83%	430	10.52%	480	10.26%
281	11.68%	331	11.20%	381	10.82%	431	10.51%	481	10.26%
282	11.67%	332	11.20%	382	10.82%	432	10.51%	482	10.25%
283	11.66%	333	11.19%	383	10.81%	433	10.50%	483	10.25%
284	11.65%	334	11.18%	384	10.80%	434	10.50%	484	10.24%
285	11.64%	335	11.17%	385	10.80%	435	10.49%	485	10.24%
286	11.63%	336	11.16%	386	10.79%	436	10.49%	486	10.23%
287	11.62%	337	11.15%	387	10.78%	437	10.48%	487	10.23%
288	11.61%	338	11.15%	388	10.78%	438	10.48%	488	10.22%
289	11.60%	339	11.14%	389	10.77%	439	10.47%	489	10.22%
290	11.59%	340	11.13%	390	10.76%	440	10.46%	490	10.21%
291	11.58%	341	11.12%	391	10.76%	441	10.46%	491	10.21%
292	11.57%	342	11.11%	392	10.75%	442	10.45%	492	10.20%
293	11.56%	343	11.11%	393	10.74%	443	10.45%	493	10.20%
294	11.55%	344	11.10%	394	10.74%	444	10.44%	494	10.19%
295	11.54%	345	11.09%	395	10.73%	445	10.44%	495	10.19%
296	11.53%	346	11.08%	396	10.72%	446	10.43%	496	10.19%
297	11.52%	347	11.07%	397	10.72%	447	10.43%	497	10.18%
298	11.51%	348	11.07%	398	10.71%	448	10.42%	498	10.18%
299	11.50%	349	11.06%	399	10.71%	449	10.42%	499	10.17%
300	11.49%	350	11.05%	400	10.70%	450	10.41%	500	10.17%

Note: The coincidence factors in Table 5 are based on hot water storage recovery under temperature control only.

Appendix 2. Data for pump price approximation

Source Grundfos product catalogue:

[https://product-](https://product-selection.grundfos.com/catalogue.html?qcid=465278232&time=1565192195993)

[selection.grundfos.com/catalogue.html?qcid=465278232&time=1565192195993](https://product-selection.grundfos.com/catalogue.html?qcid=465278232&time=1565192195993)

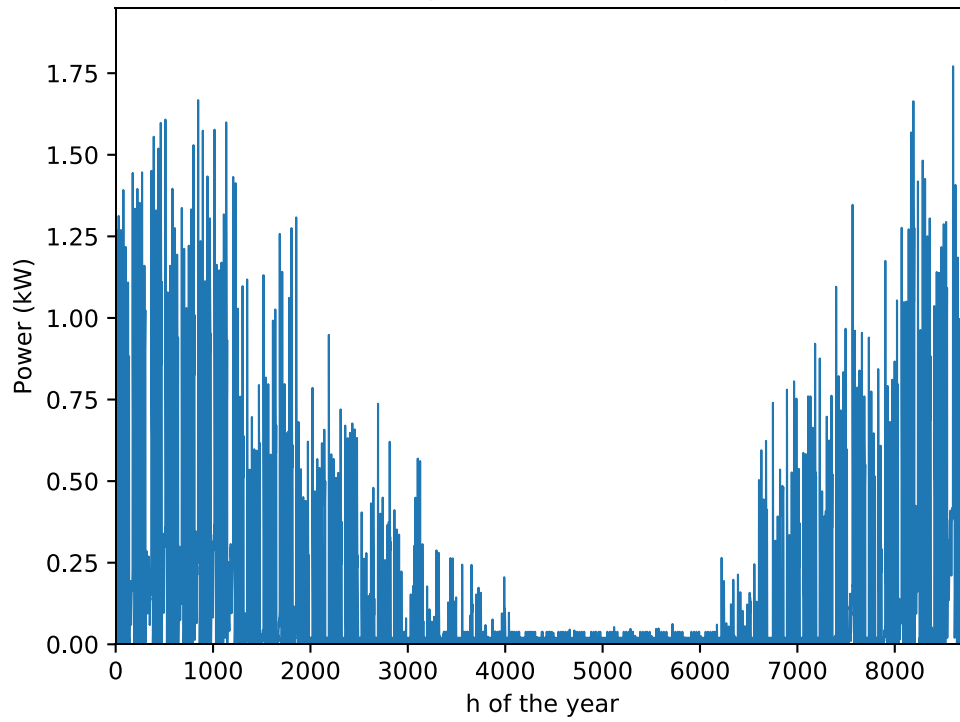
All prices are rounded. If multiple pump models fitted, the average price was taken.

Price [GBP]	Head [m]				
	10	14	18	22	26
5	1030	1100	1250	1300	1300
10	1525	1525	1830	1830	2060
15	1530	1670	1940	1950	2180
20	2670	2670	1940	2170	2250
25	2400	2200	2170	3300	3070
30	2350	3000	3200	3000	3700

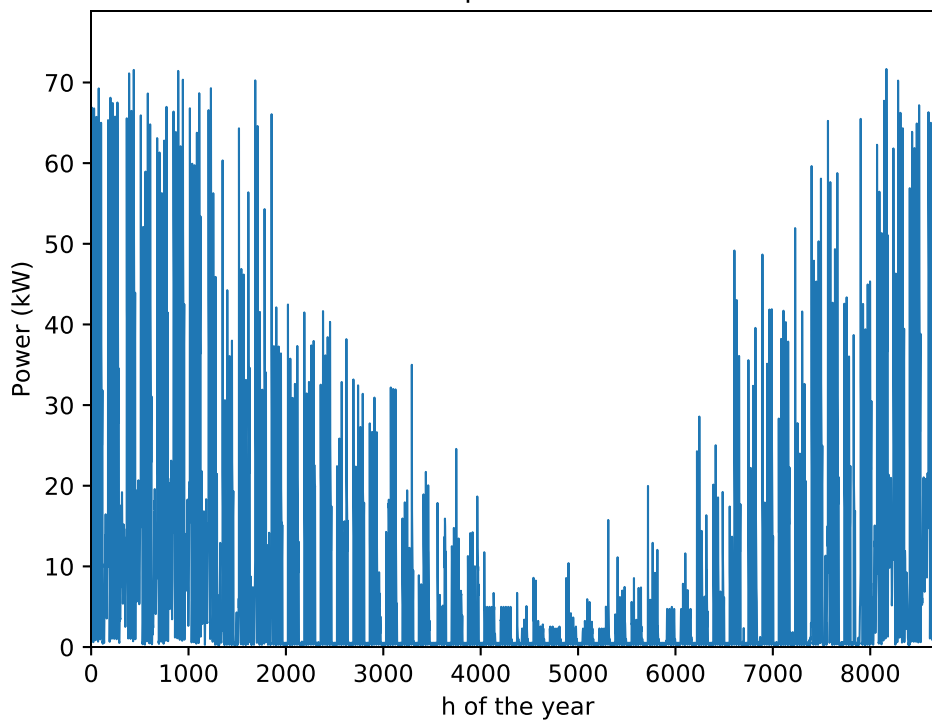
Power [W]	Head [m]				
	10	14	18	22	26
5	136.3	190.8	245.3	299.8	354.3
10	272.5	381.5	490.5	599.5	708.5
15	408.8	572.3	735.8	899.3	1062.8
20	545.0	763.0	981.0	1199.0	1417.0
25	681.3	953.8	1226.3	1498.8	1771.3
30	817.5	1144.5	1471.5	1798.5	2125.5

Appendix 3. Scaled load profiles

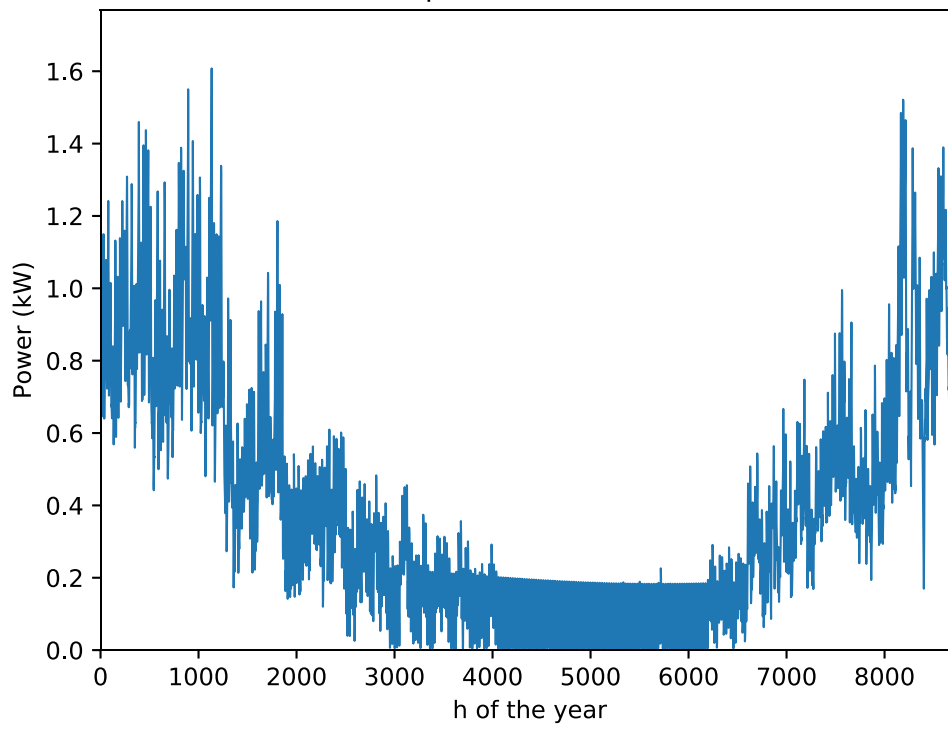
Load profile Office building



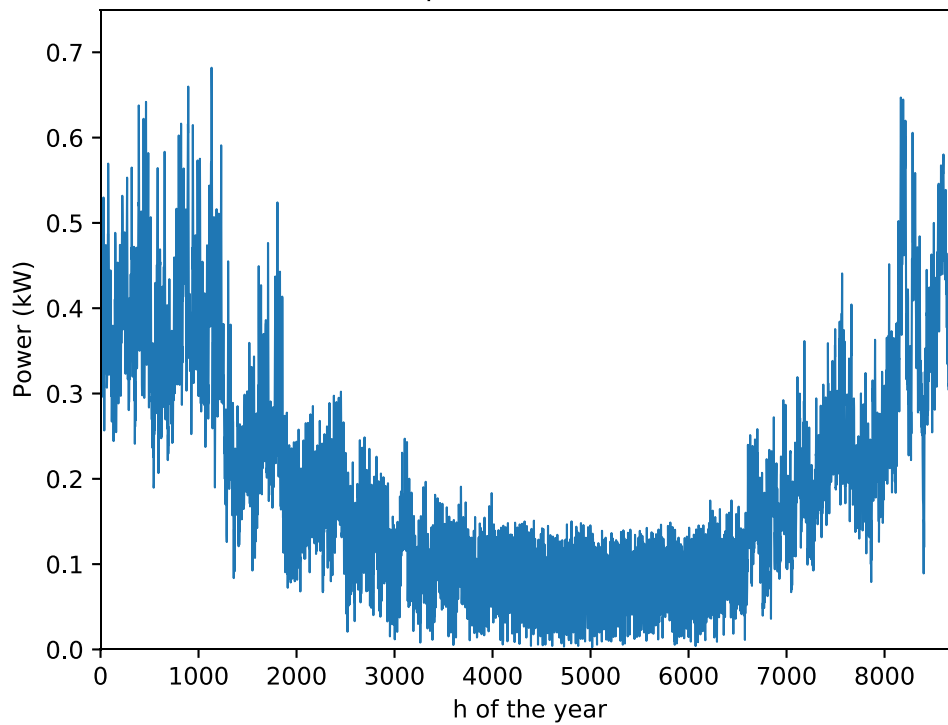
Load profile Public



Load profile Residential 1



Load profile Residential 2



Appendix 4. Worked example – “demanddistribution.txt”

Pipe 1.0:		Pipe 3.0:	
Hospital	0	Hospital	0
Office building	50	Office building	100
Public	1	Public	0
Residential 1	40	Residential 1	0
Residential 2	20	Residential 2	65

Pipe 1.1:		Pipe 3.1:	
Hospital	0	Hospital	0
Office building	0	Office building	30
Public	1	Public	2
Residential 1	15	Residential 1	25
Residential 2	70	Residential 2	15

Pipe 1.2:		Total numbers:	
Hospital	0	Hospital	1
Office building	45	Office building	310
Public	0	Public	3
Residential 1	15	Residential 1	80
Residential 2	40	Residential 2	220

		Annual Energy demands per unit:	
Pipe 2.0:		Hospital	1125000.0 kWh
Hospital	1	Office building	1500.0 kWh
Office building	85	Public	700000.0 kWh
Public	0	Residential 1	3300.0 kWh
Residential 1	0	Residential 2	1650.0 kWh
Residential 2	10		

Appendix 5. Worked example – “pipeparameters.txt”

Pipe 1.0:
Dimension: DN125
Pipe length: 400.00 m
Max. Power: 1529.25 kW
Max. volume flow: 52.66 m³/h
Max. flow velocity: 1.06 m/s
Max. pipe friction: 63.53 Pa/m
Price: £520,000.00

Pipe 1.1:
Dimension: DN100
Pipe length: 100.00 m
Max. Power: 677.57 kW
Max. volume flow: 23.33 m³/h
Max. flow velocity: 0.72 m/s
Max. pipe friction: 37.84 Pa/m
Price: £121,250.00

Pipe 1.2:
Dimension: DN40
Pipe length: 75.00 m
Max. Power: 89.99 kW
Max. volume flow: 3.10 m³/h
Max. flow velocity: 0.59 m/s
Max. pipe friction: 77.90 Pa/m
Price: £64,687.50

Pipe 2.0:
Dimension: DN80
Pipe length: 150.00 m
Max. Power: 500.74 kW
Max. volume flow: 17.24 m³/h
Max. flow velocity: 0.90 m/s
Max. pipe friction: 80.71 Pa/m
Price: £168,750.00

Pipe 3.0:
Dimension: DN100
Pipe length: 300.00 m
Max. Power: 914.41 kW
Max. volume flow: 31.49 m³/h
Max. flow velocity: 0.97 m/s
Max. pipe friction: 68.92 Pa/m
Price: £363,750.00

Pipe 3.1:
Dimension: DN100
Pipe length: 200.00 m
Max. Power: 733.71 kW
Max. volume flow: 25.26 m³/h
Max. flow velocity: 0.78 m/s
Max. pipe friction: 44.37 Pa/m
Price: £242,500.00

Total price: £1,480,937.50

Appendix 6. Worked example – “pumpparameters.txt”

Pump(s) main branch 1:	
Number of pumps:	3
1 pump(s) for redundancy	
Max. volume flow per pump:	26.33 m ³ /h
Hdr. Power (eff=1):	551.53 W
Pump head:	15.37 m
Price per pump:	£1,636.66

Pump(s) main branch 2:	
Number of pumps:	3
1 pump(s) for redundancy	
Max. volume flow per pump:	8.62 m ³ /h
Hdr. Power (eff=1):	148.73 W
Pump head:	12.66 m
Price per pump:	£1,204.33

Pump(s) main branch 3:	
Number of pumps:	3
1 pump(s) for redundancy	
Max. volume flow per pump	15.74 m ³ /h
Hdr. Power (eff=1):	309.07 W
Pump head:	14.41 m
Price per pump:	£1,376.42

Total price:	£12,652.24