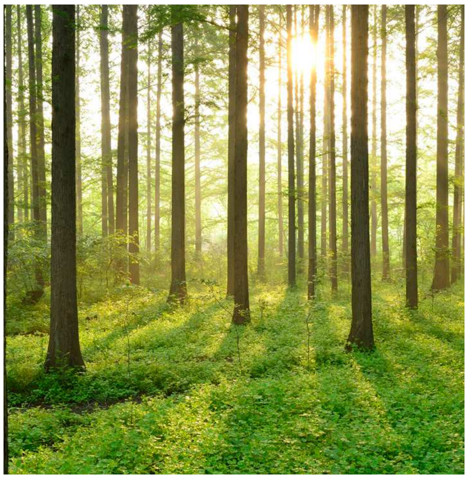
THE VALUE OF FLEXIBLE HEAT DEMAND

REPORT 2019:565



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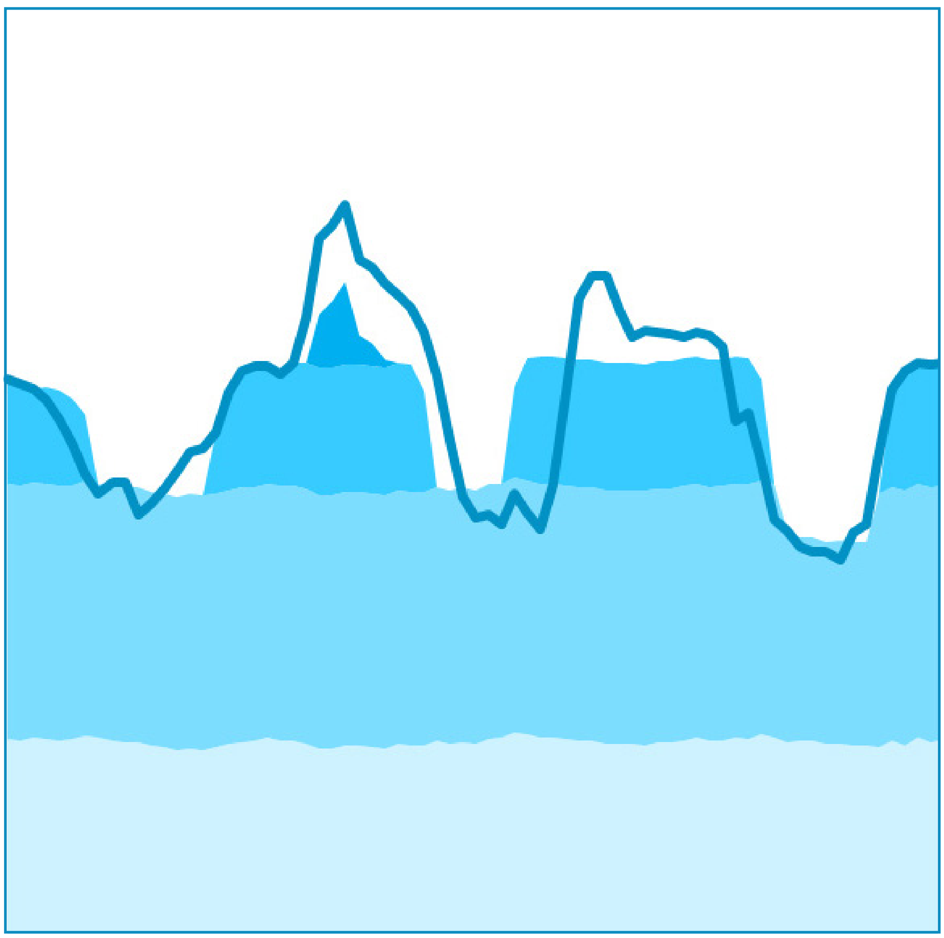

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The value of flexible heat demand

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Preface

The project *The value of flexible heat demand* (original title of the Swedish report: *"Värderingsmodell för efterfrågeflexibilitet"*) **has developed an important tool for quantifying the benefits of demand flexibility in buildings connected to district heating grids. This is a valuable step for enabling district heating companies and property owners to make decisions about investments in the technology required to enable flexibility and to be able to share the benefits that the technology provides. The extensive analysis carried out in the project also includes an analysis of what types of district heating grids that benefit the most from flexible demand, and in which situations they benefit.**

The project was led by Johan Kensby at Utilifeed together with Linnea Johansson, Samuel Jansson, Jens Carlsson. Oskar Räftegård at RISE has contributed with validation of the model for borehole storage.

A focus group consisting of Holger Feurstein (ordförande) Kraftringen; Daniel Nyqvist, Norrenergi; Joakim Holm, Tekniska Verken i Linköping; Cecilia Ibánez-Sörenson, Vattenfall R&D; Tommy Persson, E.ON Energilösningar AB; Maria Karlsson, Skövde Värmeverk AB; Thomas Franzén, Göteborg Energi; Per Örvind, Eskilstuna Strängnäs Energi & Miljö AB; Stefan Hjärtstam, Borås Energi och Miljö AB; Patric Jönnervik, Jönköping Energi; Erik Dotzauer, Stockholm Exergi; Lena Olsson Ingvarson, Mölndal Energi; Mathias Bjurman, Grundledningen HB has followed project and assured the quality.

The project is part of the FutureHeat program, whose long-term goal is to contribute to the vision of a sustainable heating system with successful companies that utilize new technological opportunities and where the social investments made in district heating and district cooling are utilized to the best of their ability. The project has been co-financed by the Swedish Energy Agency within the TERMO program.

The FutureHeat program is led by a steering committee consisting of Charlotte Tengborg (chair), E.ON Lokala Energilösningar AB, Lars Larsson, AB Borlänge Energi; Magnus Ohlsson, Öresundskraft AB; Fabian Levihn, Stockholm Exergi; Niklas Lindmark, Gävle Energi AB; Jonas Cognell, Göteborg Energi AB; Lena Olsson Ingvarsson, Mölndal Energi AB; Anna Hindersson, Vattenfall Värme AB; Anders Moritz, Tekniska verken i Linköping AB; Staffan Stymne, Norrenergi; Holger Feurstein, Kraftringen; Joacim Cederwall, Jönköping Energi AB; Maria Karlsson, Skövde Värmeverk AB; Sven Åke Andersson, Södertörns Fjärrvärme AB; Henrik Näsström, Mälarenergi AB and Fredrik Martinsson Energiforsk. Deputies have consisted of Peter Rosenkvist, Gävle Energi; Johan Brossberg, AB Borlänge Energi; Mats Svarc, Mälarenergi AB; Johan Jansson, Södertörn Fjärrvärme AB and AnnBritt Hansson, Tekniska verken i Linköping AB.

Fredrik Martinsson, program manager FutureHeat

Summary

There is considerable flexibility in building heating systems. With an extended system boundary that includes buildings, district heating grids, and connection to the electrical grid, a co-optimization can be performed that creates great value for both the economy and the environment. This value has been analyzed by a simulation study for six types of district heating grids for three flexibility types: thermal storage in buildings, heat source shifting: district heat – heat pump, and borehole storage connected to buildings.

The results show that district heating grids with a hot water storage tank can reduce their variable operating cost by 1.8–4.4% by utilizing buildings that account for 20% of the heat demand in the network as thermal storage. In district heating grids without a hot water storage tank, this value is almost doubled (3.2 –8.1%). At the same time, CO2e (carbon dioxide equivalent) emissions can be reduced by 0.3–1.4 kton for a district heating grid with an annual heat output of 500 GWh.

Based on a study of the building stock in four Swedish cities, a district heating grid with an annual heat output of 500 GWh should be connected to about 81 properties that also have exhaust air heat pumps, which is by far the most common installation of heat pump combined with district heat. If these heat pumps are controlled as part of a total optimization of the district heating grid (instead of merely serving as a base load), the entire operating expenses of the combined system can be reduced by 220–1,120 tSEK/year. If distributed per utilized heat pump, this corresponds to 2.7–13.8 tSEK/year or 120–610 tSEK per year and MW adjustable heat output in heat pumps in buildings. At the same time, CO2e emissions are reduced by 0.5–2.3 kton/year.

Borehole storage connected to buildings that are charged with district heating and the borehole storage then provide space heating systems in buildings directly with heat without a heat pump (domestic hot water demand is supplied directly with high temperature district heat) also has increased value if it is controlled as part of a co-optimization with the district heating grid. The contribution to reducing operational cost in the co-optimization case increases by 36–133%, and CO2e emissions are also further reduced.

The three types of demand flexibility that are studied fill different roles in the optimization of district heating systems, and there is (almost) no diminishing return from investing in several of them.

Demand flexibility can also be used to reduce the need for production and distribution capacity in district heating grids. This also applies to district heating grids that already have a hot water storage tank. Thermal storage in buildings that account for 20% of the heat demand with an increased operational range compared to normal optimization (variation in indoor temperature increases from 1°C to 3°C) can reduce capacity requirements by 9.5%. Only alternative investment in a hot

water boiler to cover this capacity requirement amounts to 277 tSEK per building utilized as thermal storage in this example.

Table of Contents

1 Introduction

There is a great focus currently on reducing energy use in buildings, for both economic and environmental reasons. Both cost and the environmental impact of the generated energy used in buildings vary constantly, over the year as well as over the day. This variation applies to the electricity grid as well as to most district heating (DH) grids. Therefore, *when* buildings use energy is an important factor, not just *how much* energy they use.

Today, neither energy price models nor environmental accounting encourages favorable energy usage patterns from a system perspective that takes into account when energy is used. However, there is considerable flexibility for heating systems in buildings, thanks to technical solutions as well as thermal inertia. There is thus a potential for expanding system boundaries and co-optimizing heating systems in buildings with the DH grid and the electricity grid. This study analyzes this potential from the economic and environmental perspectives.

Flexible heat demand in DH grids is a broad concept in this study that includes all heat demand that has a degree of freedom in time, quantity, and/or source. More simply put, it describes all heat demand that can be flexibly controlled with acceptable consequences for the end user. Three types of flexibility have been studied:

Thermal energy storage in buildings utilizes the thermal inertia of buildings as a thermal storage. By supplying heating systems in buildings with a little more heat than default operation at certain times and a little less heat than default at other times, it is possible to move the heat load in time. The buildings utilized then function as thermal storage, and heat is stored in radiator systems, the building structure, internal surface layers, furniture, etc. In many buildings, it is possible to store a significant amount of thermal energy without causing significant variations in indoor temperature.

Heat source shifting: district heat/heat pump refers to buildings that have both district heat and a building heat pump (BHP) as heat sources and that switch their priority order depending on marginal cost for electricity and district heat generation. BHPs are usually prioritized, primarily because property owners usually have (at least on a monthly basis) fixed prices for electricity and district heat, with the result being that heat from the BHP usually has the lowest cost. If BHP control is optimized with a larger system perspective that includes alternative heat generation in DH grids as well as spot prices for electricity, the BHP can be a valuable flexibility resource in the electric grid and the DH grid.

Borehole storage connected to buildings (and other types of long-term storage) can be used as a flexibility resource. Previous studies have shown a potential for seasonal storage of district heat in boreholes, where the heat is utilized directly for space heating in buildings (without a heat pump), while the building's hot tap water demand is met by high-temperature district heat. This concept could have even greater potential if the flexibility of the borehole storage can be controlled in a DH grid.

All DH grids have different conditions that can greatly affect the value of flexible heat demand. For example, how much the marginal cost of heat generation varies during the day has a significant impact on the value of short-term thermal energy storage (TES). In addition, flexibility is already present in many DH grids in the form of a hot water storage tank, which affects the value of adding flexibility on the demand side. It is worth mapping how valuable flexible heat demand is in different types of DH grids. This is because investment should be prioritized in DH grids with the greatest value, and each grid should invest in the most profitable flexibility (given the local conditions) or should instead invest in better alternatives. In order to analyze this, a number of archetype heat grids were created in order to reflect a large portion of Sweden's DH grids.

The purpose of the project is to give DH companies an accurate estimate of the value that the various types of demand flexibility can create in their DH grids. The goal is that this information will lead to more DH companies making investments in demand flexibility that benefit both the environment and the economy for DH companies as well as their customers.

2 Theory, method, and implementation

This is a simulation study in which different types of demand flexibility are simulated for six different archetype heat grids. Three years of production optimization are simulated for all the heat grids. Simulations are then run both without flexibility (reference case) and with different combinations of flexible demand. The resulting heat generation profiles are then analyzed using a number of key performance indicators for the different simulation cases. These key performance indicators are measures of the economic and environmental impact on the different DH grids of the types of demand flexibility studied.

It is important to keep in mind when reading the report that it describes the results of a maximum potential analysis. The results shown are thus the total savings potential that can be achieved through utilizing flexibility. Examples of business models that distribute this value between DH companies, building owners, and possibly electricity traders are discussed in Chapter 6 Discussion.

2.1 ARCHETYPES OF DISTRICT HEATING GRIDS

The analysis is based on six types of heat grids, which have been selected because together they represent a large proportion of Swedish DH grids. These six archetypes consist of three different fuel mixes, each of which is analyzed with and without a hot water storage tank, creating a total of six types of heat grids.

The three fuel mixes are based on the average fuel mix of all Swedish heat grids, shown in

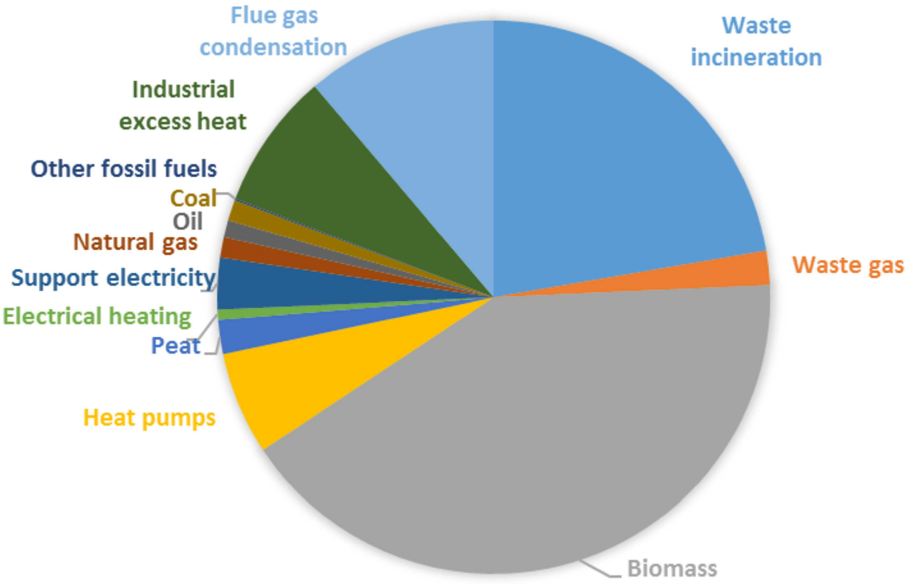


Figure 1. A typical DH grid does not include an as wide a set of fuels and technologies as that represented in the national average. For this reason, the three fuel mixes are based on the national average, but different sources of heat are given higher weightage.

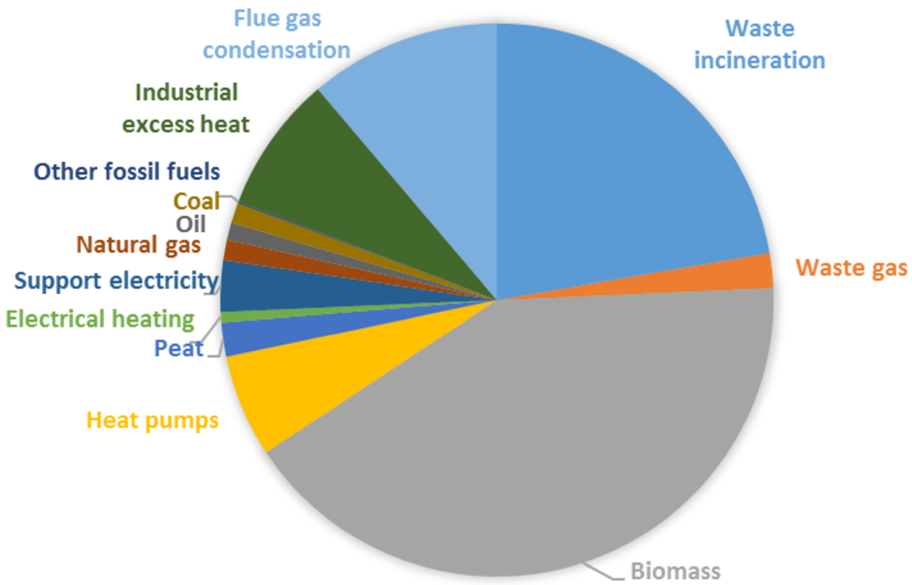


Figure 1. District heating fuel mix in Sweden 2017 (Khodayari, 2017)

All archetype heat grids have an annual average heat generation of 500 GWh and the same load profile. The reason for this is that the number of heat grids analyzed needs to be limited, and the fuel mix has a much greater impact on the value of flexibility than grid size does.

The three different fuel mixers have all been equipped with six heat only boilers (HOB), which are described in Table **1**. The oil and gas that fuel the heat only boilers are assumed in this report to be of fossil origin. Startup cost refers to the extra cost mainly related to lower efficiency when a boiler is started. The variable operational cost is per MWh of useful heat and includes fuel cost, variable maintenance cost, energy tax, carbon dioxide tax, and emission allowances. Taxes are calculated according to the 2019 tax table. The efficiency of all HOBs is set to 0.9, assuming that none of the boilers have flue gas condensation, with the reasoning that flue gas condensation is utilized so little that it is not worth the investment. It is probably realistic to have flue gas condensation on boilers that use wood chips and wood pellets as fuel, but these have not been included in this study.

Table 1. Description of the six heat only boilers present in all heat grids studied

	HOB Wood chips	**HOB Wood pellet**	**HOB Gas 1**	**HOB Gas 2**	**HOB Oil 1**	**HOB Oil 2**
Installed power [MW]	10	5	20	10	40	10
Efficiency	0.9	0.9	0.9	0.9	0.9	0.9
Startup cost [tSEK]	15	10	6	4	10	6

Variable operational cost [SEK/MWh]	210	390	940	940	1150	1150

2.1.1 Fuel mix: Extra combined heat and power

The first fuel mix is called "extra combined heat and power" and has, in addition to the six HOBs, a great deal of combined heat and power (CHP) with biomass (wood chips) as fuel. Two types of heat grid are based on this heat source, one with and one without a hot water storage tank. The variable operating cost for archetype grids with this fuel mix is 99.7 MSEK/year with no hot water storage tank and 92.7 MSEK/year with a hot water storage tank.

The distribution of installed power and generated energy for the extra combined heat and power fuel mix is given in Table **2**. The heat sources are categorized in HOBs with biomass fuel, HOBs with fossil fuel, and CHP with biomass fuel. The total installed heating power is specified, as is which part of it is achieved by excluding electricity production (bypass). The heat energy generated in the network for the different heat sources is an average of the three simulated years.

Table 2. Installed power and heat energy generated for extra combined heat and power fuel mix

	HOB Biomass	HOB Fossil	CHP Biomass
Max heat output	15.0 MW	80.0 MW	At max electricity generation: 62.5 MW heat 21.0 MW electricity At bypass-operation (no electricity): 83.5 MW heat
Share of max heat output	8.4%	44.8%	46.8% Whereof extra power at bypass-operation: 11.8%
Share of yearly heat generation Heat grid without hot water tank	8.6%	2.5%	88.9%
Share of yearly heat generation Heat grid with hot water tank	8.5%	1.8%	89.7%

Figure 2 shows heat generation for this archetype heat grid with and without a hot water storage tank during a simulated year. Heat from building heat pumps (BHP) is included in all figures to present how their control affects the demand for district heat. Their total heat generation is 10.4 GWh/year (average for the period 2015–2017).

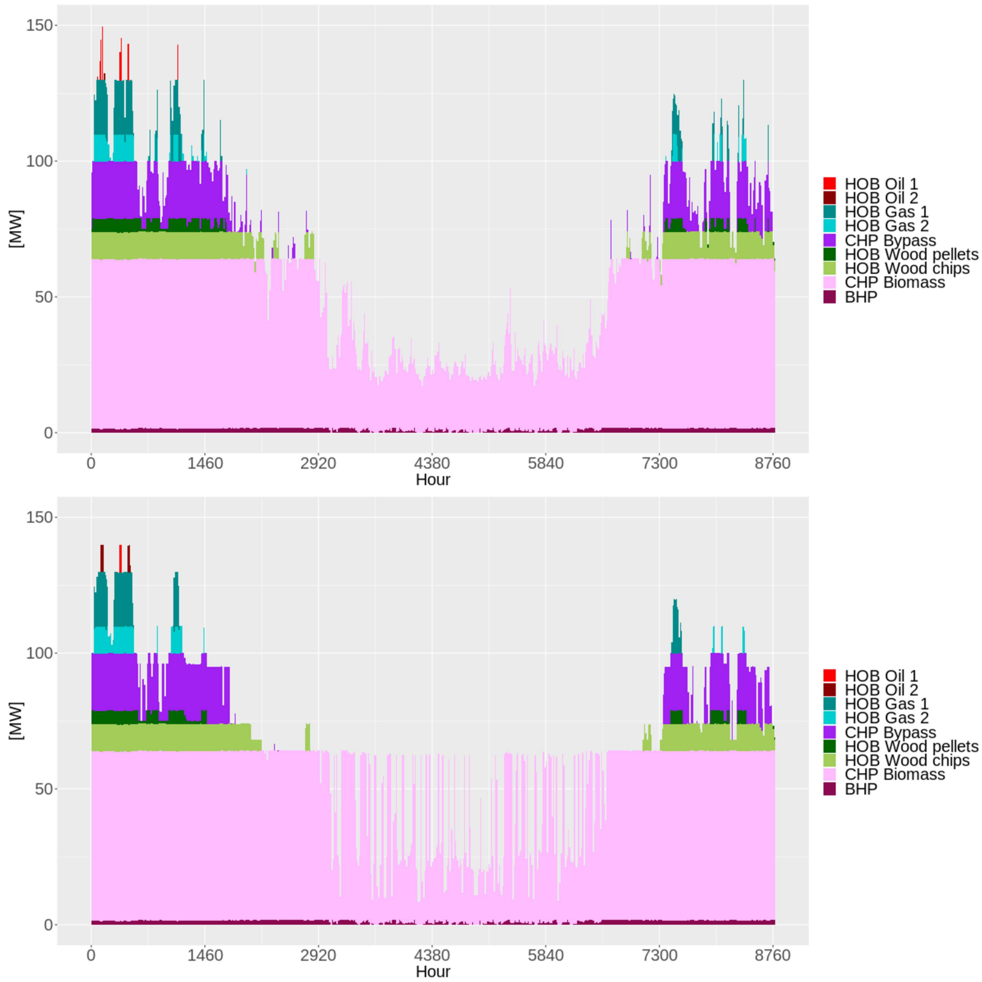


Figure 2. Simulated heat generation for 2016, no flexible heat demand
Upper figure: Archetype: CHP (extra combined heat and power, no storage tank)
Lower figure: Archetype: CHP S (extra combined heat and power, storage tank)

2.1.2 Fuel mix: Extra grid heat pump

The second fuel mix is called "extra grid heat pump" and, like the other two fuel mixes, has a CHP unit with biomass fuel. In addition, however, a large part of the installed heat generation capacity is in the form of heat pumps connected to the heat grid (GHP). The proportion of heat from the GHPs corresponds to four times the Swedish national average for heat grids. In this fuel mix, there are two GHPs of 20 MW heat output each, with coefficient of performance (COP) of 2.8 and 3.3, respectively. The variable operational cost for archetype heat grids with this fuel mix is 109.1 MSEK/year without a hot water storage tank and 104.6 MSEK/year with a hot water storage tank.

The distribution of installed heating power and generated heat energy is given in Table **3**. The heat sources are categorized as HOBs with biomass fuel, HOBs with fossil fuel, CHP with biomass fuel and GHP. The heat generated is an average of three simulated years.

Table 3. Installed power and generated heat energy for extra grid heat pump fuel mix

	HOB Biomass	HOB Fossil	CHP Biomass	GHP
Max heat output	15.0 MW	80.0 MW	At max electricity generation: 33.6 MW heat 11.3 MW electricity At bypass-operation (no electricity): 44.9 MW heat	40.0 MW
Share of max heat output	8.3%	44.5%	25.0% Whereof extra power at bypass-operation: 6.3%	22.2%
Share of yearly heat generation Heat grid without hot water tank	11.4%	2.2%	55.7%	30.7%
Share of yearly heat generation Heat grid with hot water tank	11.5%	1.7%	56.1%	30.7%

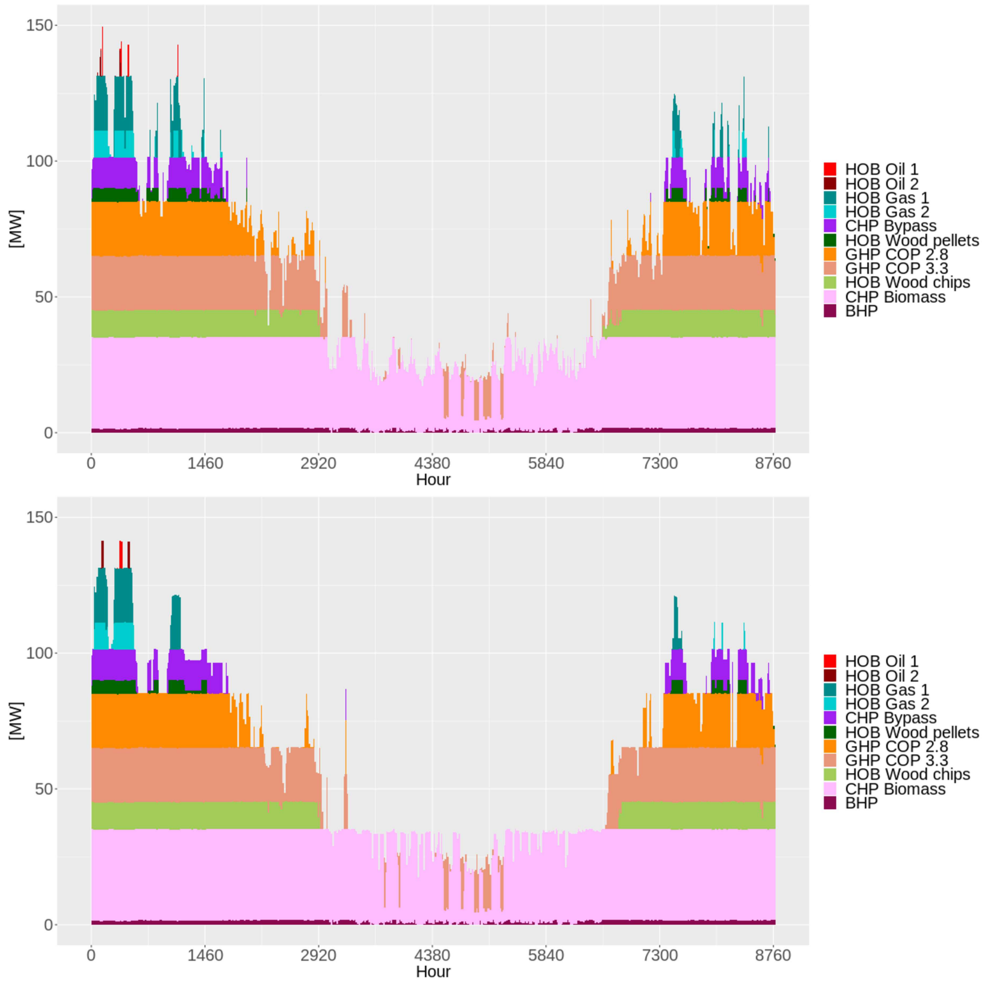


Figure 3. Simulated heat generation for 2016, no flexible heat demand

Upper figure: Archetype: GHP (extra combined heat and power, no storage tank)

Lower figure: Archetype: GHP S (extra combined heat and power, storage tank)

Heat grid with satellite

The extra grid heat pump fuel mix has also been simulated in an area in the heat grid in which transmission capacity is limited. This means that there is a smaller grid, or satellite, connected the main grid. This satellite represents 10% of the entire grid's heat demand. The maximum transmission capacity between the satellite and the rest of the network is set to 8.5 MW. In the simulation, HOB Oil 2 has been allocated to the satellite. This means that when the heat demand in the satellite exceeds 8.5 MW (which it does when the entire grid's demand exceeds 85 MW), the oil boiler needs to be started even if there is generation capacity with lower marginal cost available centrally in the grid. This special case of the extra grid heat pump archetype heat grid is used to study the possible increased value of flexibility in satellites, and the results are presented in Chapter: 4.5 Managing transmission .

2.1.3 Fuel mix: Extra excess heat

The third fuel mix is called "extra excess heat" and, like the other two fuel mixes, it has a share of CHP with biomass fuel. In addition, a large part of the heat is recovered excess heat. The excess heat is assumed to be heat where the variable operating cost is negligible. Two common cases of excess heat are garbage incineration and excess heat from industrial processes. In this report, the cost of surplus heat is 20 SEK/MWh, which only reflects extra pumping cost and variable maintenance cost associated with utilizing the excess heat. The variable operating cost for archetype heat grids with this fuel mix is 47.0 MSEK/year without a hot water storage tank and 42.4 MSEK/year with a hot water storage tank.

The distribution of installed heating power and generated heat is given in Table **4**. The heat sources are categorized as HOBs with biomass fuel, HOBs with fossil fuel, CHP with biomass fuel, and excess heat. The heat generated is an average of three simulated years.

Table 4. Installed power and generated heat energy for extra excess heat fuel mix

	HOB Biomass	HOB Fossil	CHP Biomass	Excess heat
Max heat output	15.0 MW	80.0 MW	At max electricity generation: 33.6 MW heat 11.3 MW electricity At bypass-operation (no electricity): 44.9 MW heat	40.0 MW
Share of max heat output	8.3%	44.5%	25.0% Whereof extra power at bypass-operation: 6.3%	22.2%
Share of yearly heat generation Heat grid without hot water tank	6.7%	2.2%	32.0%	59.1%
Share of yearly heat generation Heat grid with hot water tank	6.5%	1.7%	32.0%	59.8%

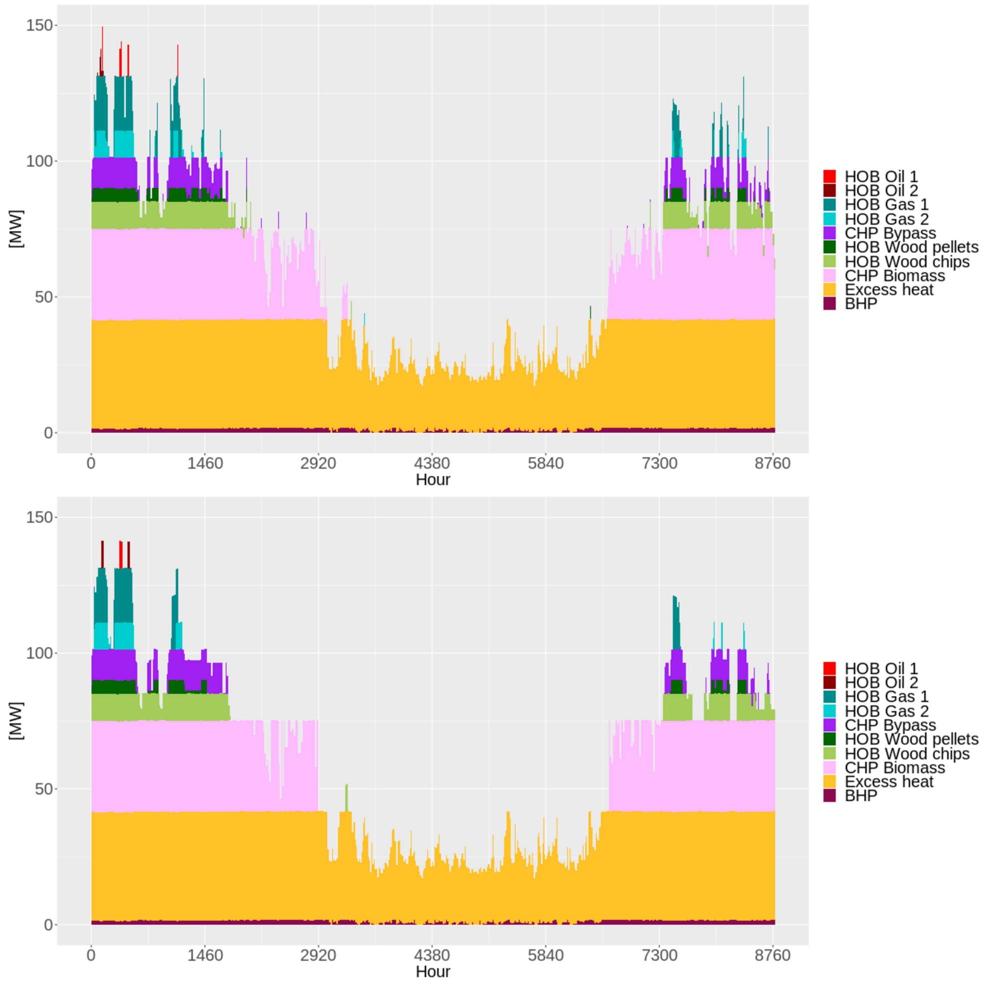


Figure 4. Simulated heat generation for 2016, no flexible heat demand

Upper figure: Archetype: EH (extra excess heat, no storage tank)

Lower figure: Archetype: GHP S (extra excess heat, storage tank)

2.2 THERMAL STORAGE IN DISTRIBUTION GRID

All simulated heat grids are assumed to have the opportunity to utilize the distribution grid as thermal storage. Since the analysis uses demand profiles that are based on measured heat generation data, this opportunity for thermal storage is already partly included in the heat demand profile. Therefore, cautious assumptions have been made about the possibility of network storage. It is assumed that it is possible to adjust the supply temperature by 5°C and that the median time for the water to reach sub-stations is three hours. This gives an output of 8 MW and a capacity of 24 MWh. Furthermore, it is assumed that the distribution losses increase proportionally when the supply temperature increases and that two-thirds of the annual distribution loss of 10% comes from the supply pipes in the distribution network.

2.3 HOT WATER STORAGE TANK

DH grids that account for about three quarters of the heat supply in Sweden have a hot water storage tank accumulator tank (Werner, 2017). The average size for these DH grids is 7 m^3 per TJ sold heat. We assume that the studied archetype heat grids in this project (500 GWh generated heat = 450 GWh sold heat) have this ratio, which translates into a storage tank size of 11,300 m^3 or 500 MWh.

Hot water storage tanks in DH grids primarily have the following two uses:

- **Flexibility resource for heat generation:** The storage tank acts as a type of flexibility that enables more economical and environmental operation of heat generation facilities. For example, the storage can be utilized to operate boilers with more even load, to avoid having to start an extra boiler for a few hours, or to allocate operation of CHP to hours with the highest electricity prices. The level of advanced solutions that are used for this varies between DH companies, but the basic idea is the same regardless of whether optimization software is used or whether the operation relies on rules of thumb and operator experience.
- **Power reserve:** Hot water storage tanks play an important role as power reserve in most heat grids in which they are in operation. In the case of temporary loss of heat generation capacity in one or more boilers, the heat supply can be managed since there is always a certain amount of heat stored. Storage tanks are therefore a complement to backup heating power that can handle shorter production losses or other situations that arise.

In order to use a hot water storage tank as backup heating power, the energy level in the tank needs to be kept above a minimum. In this project, we set this level to 50% for November–February and 25% for June–August. In between, the lowest level varies linearly, as shown in

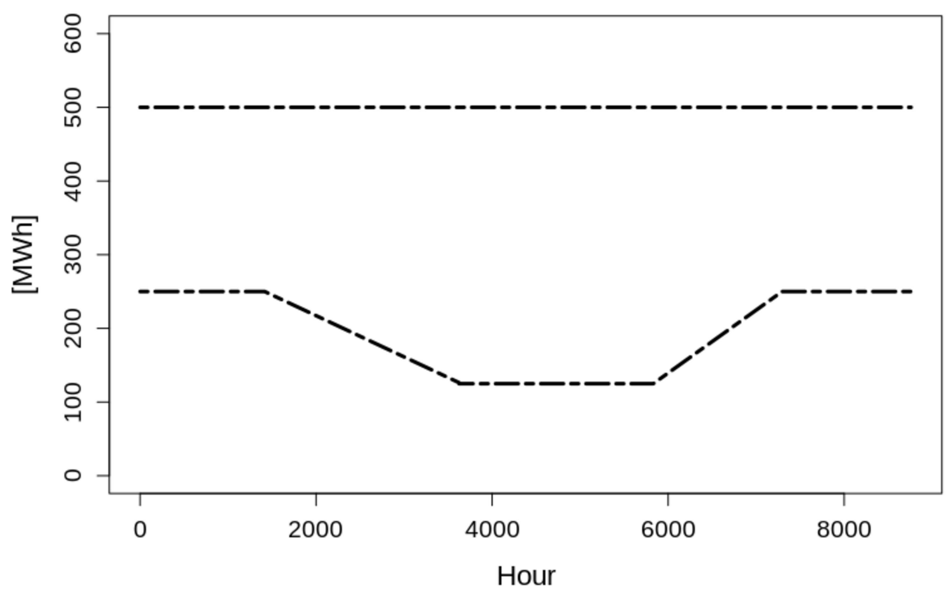


Figure 5. This means that the energy level may be varied from the lowest level up to 100% during all hours. This flexibility is used in optimization on the same premises as the demand flexibility studied in this work. In practice, this means that the heat storage capacity that can be used in the storage tank varies between 250 MWh in the winter and 375 MWh in the summer.

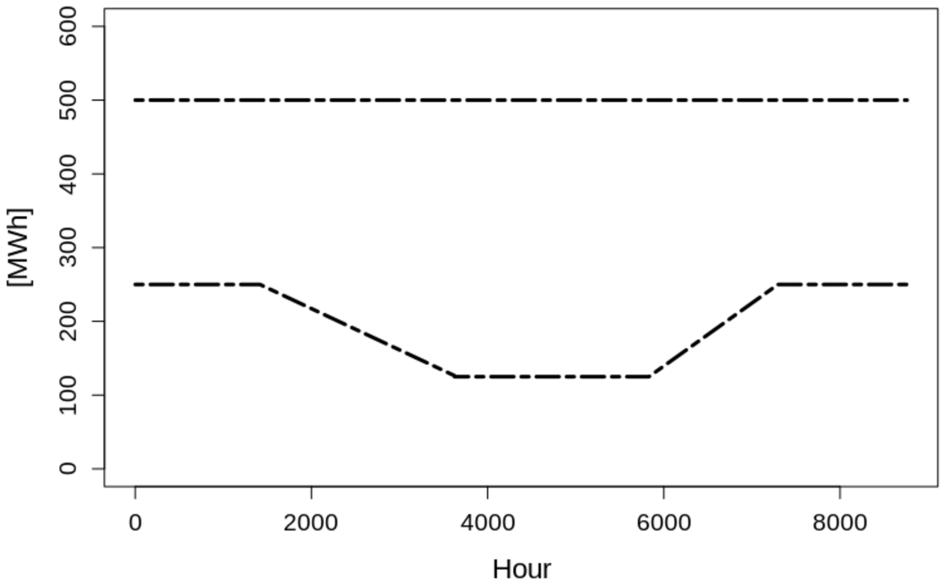


Figure 5. Maximum and minimum allowed amount of stored heat in the storage tank in normal operation during the year

Heat losses from the storage tank are calculated according to a model with parameters that describe mixing during charging and discharging and transmission losses through insulation. If the storage tank is filled to 100% and then emptied after exactly one week, the loss is 2.7% of the energy content.

All three fuel mixes are now each represented by two archetype heat grids, one without and one with a hot water storage tank. A list of the archetype heat grids and their abbreviations is presented in Table **5**.

Table 5. List of studied archetype heat grids

Abbreviation	**Description**
CHP	Extra combined heat and power *without* storage tank
CHP S	Extra combined heat and power *with* storage tank
GHP	Extra grid heat pump *without* storage tank
GHP S	Extra grid heat pump *with* storage tank
EH	Extra excess heat *without* storage tank

EH S	Extra excess heat *with* storage tank

2.4 HEAT GRIDS NOT REPRESENTED BY THE ARCHETYPE HEAT GRIDS

The analysis is based on six archetype heat grids that together represent a very large proportion of Swedish DH grids. By processing in different ways, other heat grids can be represented. Some examples of processing are presented in Table **6** and should give a good picture of the value of flexible heat demand for many heat grids; it is worth noting that, for best results, a specific study is required of the heat grid in question. A compilation of results for each archetype heat grid can be found in Appendix A.

Table 6. Ways to process the results to represent more heat grid types

Deviation from archetype heat grid	Processing method
Heat grid with no CHP	Exclude revenues from sold electricity
Garbage incineration is the source of excess heat	Garbage often has a negative fuel price, which means that this has to be excluded from the total operating cost. If a CHP is fueled by garbage, a calculation of the amount of electricity generated and the income from selling it must also be made.
Peak HOB is fueled with biogas or bio oil	The difference is mainly that the environmental benefits from reducing peak demand are reduced when non-fossil fuel is used to cover peak demand.
Larger or smaller heat grids	If the heat grid is smaller or larger than 500 GWh/year, scaling absolute values in the results proportionally to the annual generation should be sufficient.

2.5 FLEXIBILITY: THERMAL STORAGE IN BUILDINGS

The utilization of thermal storage in buildings in DH grids is possible thanks to the buildings' thermal mass. A larger thermal mass (in a building with the same isolation level) requires a larger amount of energy to raise the temperature by, for example, 1°C. For buildings with a large thermal mass, this means that it will take many hours (or even days) after the heating system is switched off before the indoor temperature drops to an unsatisfactorily low level.

Thanks to this thermal mass, heat load can be shifted in time by alternately supplying more or less heat than that added in a normal case (with no thermal storage utilization) and at the same time keeping the variation in indoor temperature within such a span that the residents do not notice, while meeting the applicable standard for thermal comfort (ISO7730, 2005). The thermal mass utilized for thermal storage in buildings does not consist solely of the mass of the structure itself. It also includes circulating water in the heating system, furniture, and the air in the building, which make a more or less significant contribution to the total usable thermal mass in this context.

The parameters for the model used to describe thermal storage in buildings are based on thermal response tests performed in Gothenburg, Sweden, in 2010 and 2011. These tests are described in (Kensby, et al., 2015) and the model is described in (Kensby, 2017) and (Romanchenko, et al., 2018).

The model applies a superposition principle and only describes the thermal deviation of a building compared to a normal state (which is what the thermal condition would have been if the building had not been utilized as thermal storage). The model consists of two thermal nodes that describe the thermal energy stored in the building (see Figure 6). These nodes are referred to as shallow storage and deep storage. Shallow storage represents thermal energy that has small resistance in being transferred to the air in the building. This includes the radiator system, furniture, interior layers on floors, walls, and ceilings, and the air itself. Deep storage represents the thermal energy stored in the building's structure. Deep storage has a significantly greater capacity for storing heat than shallow storage, but the maximum power for transferring heat to the air is limited. Deep storage thus cannot be used directly, but it slowly heats up if the building maintains a high indoor temperature for a longer period and then slowly emits heat over a longer period if the indoor temperature is lowered.

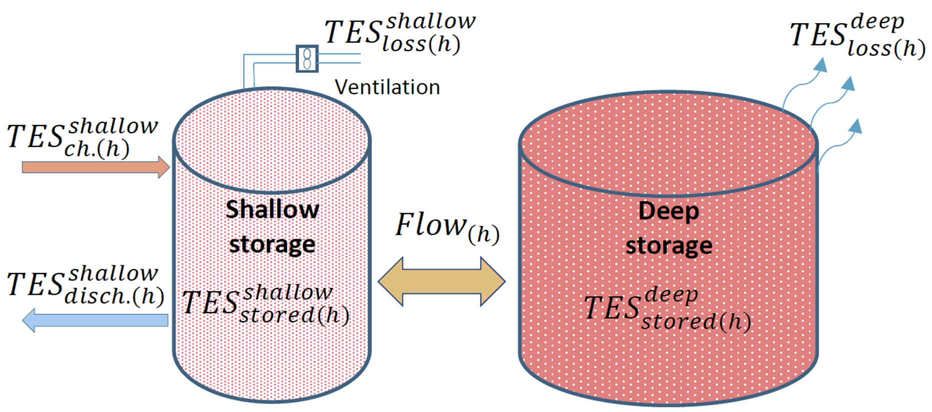


Figure 6. Schematic representation of the model for thermal storage in buildings (Kensby, 2017)

In order to estimate the potential flexibility in a heat grid with 500 GWh annual heat demand, a database of energy performance certificates for all properties (except private homes) in four Swedish cities was studied. A selection was made of properties considered suitable for thermal storage and the parameters required for the model were estimated. The estimation was based on the results from a series of previous thermal response tests. The parameters were scaled to the buildings in this study based on a number of assumptions:

Thermal storage capacity for shallow storage and deep storage (max value for TES shallow/deep storage in Figure 6) is assumed to scale linearly with the heated floor area (A-temp) in the buildings. This is because the parameters describe thermal mass, which should have a clear correlation with floor area.

An energy signature is calculated for each utilized building. The signature is estimated by allocating the annual heat demand (domestic hot water excluded) to all hours within a year proportional to how much lower the outdoor temperature is relative to a break point (17°C).

Maximum power for charging and discharging (TES shallow ch./disch. in Figure 6) is estimated for every hour and has two natural limitations. It is not possible to discharge more power than the actual heat demand in that hour in the building (that is, the building cannot deliver heat to the grid but can only reduce its heat use from its normal use). It is also not possible to charge with a power that is higher than the design power minus the heat demand in the actual hour (otherwise the design power would be exceeded, which is not possible since there is likely an upper limit on the supply temperature to the radiator system). In addition to these limitations, a higher charge power than energy signature x 5°C is also not allowed (the extra heat that is supplied to a building may have a maximum effect on the heat supply equal to how a drop in outdoor temperature of 5°C would affect the heat supply); also, the discharge power may not exceed the energy signature x 10°C (the reduction of heat that is supplied to a building may have a maximum effect on the heat supply equal to how an increase in outdoor temperature of 10°C would affect the heat supply). These two limitations are based on practical experience, and their purpose is that residents should not experience radiator heaters that are significantly warmer or colder than they expect.

Loss factors are estimated based on the assumed energy signature. An increased indoor temperature of 1°C is assumed to give an equal increase in heat transfer to the outside as a reduction of outdoor temperature by 1°C.

2.6 FLEXIBILITY: HEAT SOURCE SHIFTING: DISTRICT HEAT – HEAT PUMP

This type of flexibility utilizes the ability to control BHPs that have both DH and BHP. Due to the fact that spot prices for electricity and marginal cost for producing heat in DH grids vary, there may be incentives for this type of control. The normal case today is that the building owner pays prices for district heat and electricity that do not fluctuate in time (at least not on less than a one-month horizon). Therefore, there is currently no incentive for building owners to control BHPs with a larger system limit than the building in mind.

Information on the BHPs installed in the studied building stock is limited to that stated in the energy performance certificates. The energy-related information that can be obtained is as follows:

- Yearly electricity use for BHPs
- Category of BHP (e.g., exhaust air, geothermal, or air-air)
- Yearly district heat usage
- Yearly heat use for hot tap water

In order to create heat pump models that describe the efficiency of the heat pumps and the maximum heat power they can supply every hour, a number of assumptions have been needed:

- All domestic hot water is generated from district heat in buildings with both heat pump and DH.
- Each building's heat demand profile has been estimated by subtracting heat use for tap water from the total heat use. The heat demand profile has then been created by distributing the remaining heat demand over the hours of the year proportional to how much colder the outdoor temperature is than 15°C (energy signature model).
- A BHP cannot supply more heat than a building's heat demand (excluding hot tap water) each hour.
- Radiator system temperatures in buildings with heat pumps have been assumed to follow the average values, based on a study of radiator temperatures in 109 buildings in Gothenburg (Jangsten, et al., 2017). Supply temperature is 64°C and return temperature is 42°C when the outdoor temperature is -16°C.
- DH and heat pumps are assumed to have a simple parallel connection according to *Chapter: 4.2.2 Värme med FV och VP parallellt* in (Boss, 2012). This means that the heat pump condenser (at maximum load) needs to maintain a temperature about 3°C higher than the radiator system's supply temperature.
- The type of compressor or its performance is estimated as a mix of three types of heat pumps: single fixed-speed compressor, dual fixed-speed compressors, and single variable-speed compressor.
- The heat pump's maximum power is then estimated backwards based on its annual electricity use and the building's assumed heat demand.

The result of these assumptions is a mix of BHPs whose efficiencies all vary over the year. Their seasonal performance factor (SPF), which is an annual average of efficiency, ranges from 2.8 to 4.1.

In the studied reference case, these BHPs are not part of the optimization, but they are instead always assumed to be switched on and supplying as much heat as possible when there is a heat demand in the buildings. This case is compared to a flexible control case in which the BHPs are treated by the optimization just like any other heat source in the heat grid. The BHPs' operating cost is then included in the optimization's target function, which then has the goal of minimizing the sum of the operating cost of the DH grid and the BHPs. The variable operating cost of the BHPs is a sum of the following:

- Nordpool day ahead spot price (hourly values)
- Electricity certificate (monthly values)
- Energy tax
- Electricity grid fee

The difference between BHPs and DH grid heat pumps (present in archetypes GHP and GHP S) is that BHPs are assumed to have a higher electricity grid fee (220

SEK/MWh compared to 100 SEK/MWh). On the other hand, a variable maintenance cost is not included for BHPs, and those heat pumps also often have better performance.

2.7 FLEXIBILITY: BOREHOLE STORAGE CONNECTED TO BUILDINGS

The value of borehole storage connected to buildings has previously been studied in the Fjärrsyn report: *Fastighetsnära säsongslagring av fjärrvärme* (Nilsson, et al., 2016). This project examined the possibility of storing heat from DH grids in boreholes during the summer and utilizing this heat directly in the heating of buildings (without a heat pump to raise the temperature) during the winter. Three building types were studied, all of which were provided with a storage of borehole fields consisting of holes drilled to ordinary depths (110–150 meters). These boreholes were fitted with standard dual U-tube collectors.

One of the buildings studied (Building 3 – Energy renovated building from the "million homes program") in the aforementioned project has also been studied as part of this project. The million homes program was a housing program in Sweden in the 1960s and 1970s as part of which a very large number of standardized tenements were built, which were typically concrete buildings of 3–5 stories. The difference in this study is that the conditions for heat generation in the DH grid are modeled in greater detail (hourly resolution), and there is an opportunity to actively control the borehole storage and utilize the flexibility it provides for better optimizing the heat generation in the DH grid. The same borehole storage is studied in this project, but the building supplied by the borehole storage has been scaled up, so now the borehole storage covers 67% of the heat demand (excluding tap water) from October–April instead of 91% as in the previous study. The reason this borehole storage has been chosen is that there should be room for flexible operation, which is hardly possible if the borehole storage covers almost the entire property's heating demand during the winter months. Three simulation cases are to be compared for all six archetype heat grids:

No borehole storage. The same reference case as for thermal storage in buildings, but the borehole storage is not available.

Borehole storage with non-flexible control. The borehole storage exists and is controlled according to a predetermined profile. This means that the storage will be charged from May to September with a constant power each month and it should be fully charged by the last day in September. From October to April, the storage is discharged according to a profile that is proportional to the building's heat demand (tap water is excluded).

Borehole storage with flexible control. The borehole storage exists, and charging and discharge of borehole storage is utilized in the optimization in order to better optimize heat generation in the heat grid. The model has some logical limitations:

- Discharge is not allowed from June to August, and charging is not allowed from November to March. This is to prevent the borehole storage from being actively used as a daily storage and constantly switching between charging and discharging.

- The stored energy in the borehole storage at the last hour each month is predetermined and is the same as for the non-flexible operation. This is a limitation in optimization, but an optimization in practical use would have such boundary conditions anyway since weather forecasts have a relatively short horizon.

These two constraints mean that the borehole storage is used according to an operating pattern that does not deviate too much from the case with non-flexible operation. The borehole storage does not fill the role of daily storage like a hot water storage tank, and it is mainly the hours and days of charge and discharge that are being shifted, but the net energy charged and discharged to and from the borehole storage is constant each month. The optimization in this project uses a simplified borehole model that consists of an energy balance for the borehole with predetermined power limitations and losses. The reason for this is that it is far too computationally demanding to include an advanced borehole model for the type of optimization performed in this project. The resulting charging profile from the simplified model has been validated in Earth Energy Designer, a proven commercial software for the design of borehole storages. Simulations in Earth Energy Designer have been performed by Oskar Räftegård at RISE (Research Institutes of Sweden).

2.8 OPTIMIZATION MODEL

In order to simulate the different archetype heat grids with and without flexibility, an "optimization model generator" has been developed. The model generator is coded in the language of JuiliaLang, which is very similar to Python but has better performance for the type of optimization problem handled in this project. A program has been created that, given a number of input files where parameters for boilers, storage tanks, and flexibility resources are specified, generates a mathematical problem. This mathematical problem is then solved using a solver from Gurobi. The solution is a plan for how all heat sources, storage tanks and flexibility resources should be controlled every hour to minimize variable operating cost. This method has been chosen because six archetype heat grids (and four real heat grids) are studied in the project, and all heat grids are simulated with and without different combinations of flexibility. Since each simulation case requires its own model, the model generator is an effective method for quickly and automatically creating the hundreds of models needed for the analysis.

All mathematical problems generated by the models are solved with the aim of minimizing variable operating cost, which is the sum of these parameters for all heat sources:

- Fuel cost
- Extra fuel cost associated with startup of boiler
- Energy tax
- Carbon dioxide tax
- Emission allowances

- Variable overhead and maintenance cost
- Cost of electricity for heat pumps in the DH grid (Nordpool day ahead spot price (hourly values) + electricity certificate (monthly values) + electricity grid fee + energy tax)
- Revenue from electricity sold from CHP is subtracted (Nordpool day ahead spot price (hourly values) + electricity certificate (monthly values))

The reason for using variable operating cost as an optimization parameter is that it is this parameter that a heating company under normal circumstances should aim to minimize in a real operating scenario. In a DH grid without flexibility or storage tank, the use of a merit order based on variable operating cost for each heat source is likely to result in a similar operation as this optimization. As soon as any type of flexibility is involved, a more sophisticated optimization is required to maximize the benefits of this flexibility.

Important aspects to keep in mind for this type of optimization include the following:

Perfect forecast: There is no uncertainty in the model and all conditions are known in advance for all hours. This applies to heat demand, electricity price, and how all heat sources perform. The consequence is that the optimization does not have any safety margins. For example, if the requirement for avoiding starting an expansive peak load HOB is that 107.2 MWh of heat be stored in a hot water storage tank at a specific point in time, then there will be exactly 107.2 MWh of heat stored at that given point. In a real world case, it would probably have been ensured that there was at least 150 MWh stored in order to be adequately sure that there is no need to start the peak load HOB. However, this applies to both reference cases without demand flexibility (but with storage tank) as well as to simulation cases with demand flexibility.

Optimization horizon: The entire optimization period is three years (2015–2017). It is too time consuming for the solver to solve the entire period as a single optimization problem. However, this is not necessary because how the system operates at a given hour has a minimal impact on optimal operation over several weeks or months. In this project, the optimization uses a rolling horizon of two months, where only the first month is used. This means, for example, that January and February 2015 are optimized together. The operating profile for January is stored as a result, and the status on 1 February 00:00 is used as the starting point for a new optimization that extends over February and March. This procedure is repeated 36 times to optimize all three years. With this method there is always a sufficiently long horizon to not influence the result and still have an optimization that can be run on a regular laptop.

2.9 DESIGN POWER

An additional value of flexible heat demand is the opportunity to reduce the design power and flow in a DH grid. This raises the possibility of reducing the fixed cost associated with investing in and maintaining capacity in heat generation and distribution.

Traditionally, design power is calculated by using an energy signature, that is, a linear regression where heat demand is expressed as a function of outdoor temperature. Based on this linear relationship, a theoretical heat demand is calculated at EOT5 (the lowest average temperature for five consecutive days over a 30-year period). Apart from the fact that this method contains significant uncertainties, it does not provide information on how the heat demand profile is shaped during the days that dictate the design power. In order to calculate how the design power can be reduced by utilizing demand flexibility, the magnitude of the design power is important as well as the duration and shape, since there are limitations to how long flexibility can be utilized (before, for example, it becomes too cold indoors).

Detailed weather data and a more advanced model, EnergyPredict, are used to develop a heat demand profile. EnergyPredict is used for modeling how energy, flow, and forward and return temperatures depend on weather parameters and calendar parameters (time of day, day of the week, and work free days). EnergyPredict has an average error for hourly values of energy of about 1% of the annual average heat demand. This is achieved through a combination of machine learning and physical models specially developed for functioning well on heating systems.

Based on measured heat demand for one year in the archetype heat grid, a model is trained with EnergyPredict and, based on this model, a heat demand profile with hour resolution is simulated based on the weather data for the years 1999–2017. EnergyPredict returns the most probable heat demand for each hour and a confidence interval (an upper value that is exceeded with 10% probability and a lower value that is exceeded with 10% probability). The periods with the maximum heat demand in a single hour, maximum average heat demand over 24 hours, and maximum average heat demand over 120 hours (five days) are studied in more detail.

The selected periods are simulated with and without the flexibility type of thermal storage in buildings in order to calculate how much the heat generation and distribution capacity can be reduced while still fulfilling the demand.

3 Available flexibility in archetype heat grids

This chapter presents a summary of the available flexibility in the archetype heat grids and the utilization cases that have been selected for simulation.

3.1 THERMAL STORAGE IN BUILDINGS

In order to study the potential flexibility in utilizing buildings as thermal storage, energy performance certificates from four Swedish cities have been combined and scaled to be representative of a DH grid with an annual heat generation of 500 GWh. Based on this material, there should be a total of 1120 non-residential properties in a DH grid. Of these properties, 790 are used for residential purposes, and these are the properties examined in this study.

The maximum deep flexibility in the properties studied is 678 MWh, and the corresponding maximum shallow flexibility is 107 MWh. Because flexibility varies greatly between different buildings, there is value in first and foremost utilizing buildings with the greatest flexibility. How the amount of flexibility depends on the number of properties utilized is shown in Figure 7.

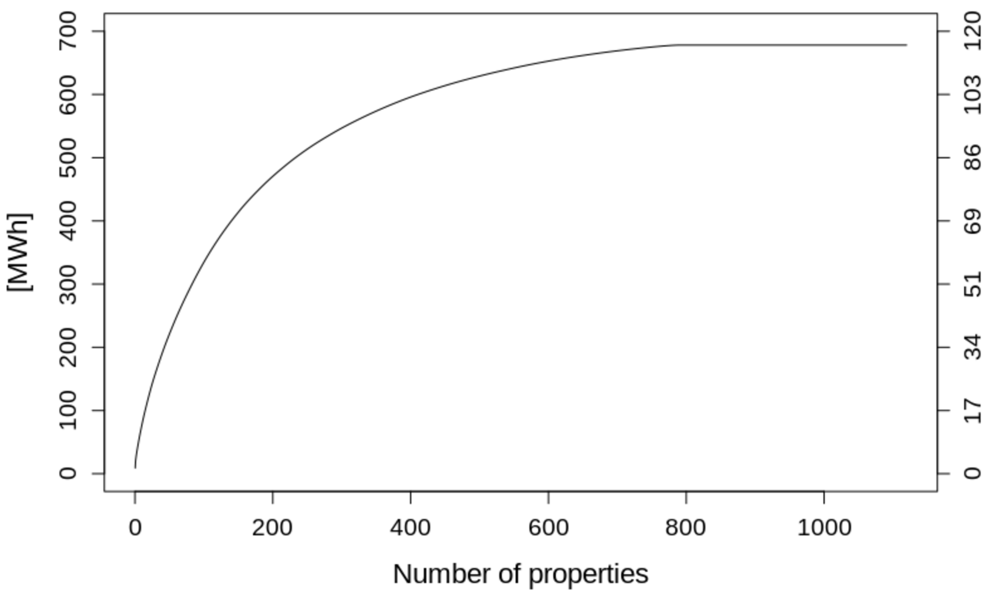


Figure 7. Total available flexibility as a function of the number of properties utilized. The left axis shows deep flexibility [MWh] and the right axis shows shallow flexibility [MWh]

This report presents simulations of two flexibility scenarios regarding flexibility in thermal storage in buildings. In the first scenario, a vast selection of the 287 largest properties has been made, corresponds to 79% of maximum possible flexibility. These properties utilize 44% of the total amount of heat generated in the grid. In the second flexibility scenario, a smaller selection of the 65 largest properties has been made, which corresponds to 38% of maximum possible flexibility. These properties account for 20% of total annual heating demand in the grid. Table **7** presents information on the properties utilized as thermal storage in the two flexibility scenarios studied.

Table 7. Properties utilized as thermal storage in the two flexibility scenarios studied

	Number of properties	Available flexibility	Annual heat demand
Flexibility case: Thermal storage in buildings 44%	287	Deep: 576 MWh Shallow: 94 MW Max power: 19 MW	220 GWh/year 44%
Flexibility case: Thermal storage in buildings 20%	65	Deep: 283 MWh Shallow: 45 MW Max power: 9 MW	103 GWh/year 20%

3.2 HEAT SOURCE SHIFTING: DISTRICT HEAT – HEAT PUMP

In order to estimate possible flexibility from heat pumps in buildings that also use district heat, energy performance certificates from four Swedish cities were combined and scaled to the archetype heat grids with an annual heat generation of 500 GWh. Almost all BHPs combined with DH are exhaust air heat pumps, and only heat pumps of that type are included in this study. Based on the study of energy performance certificates, there should be 81 exhaust air heat pumps in one archetype heat grid. The 81 buildings with these heat pumps have the following combined statistics:

- Annual district heat use: 11.6 GWh
    - Whereof hot tap water: 2.6 GWh
- Annual electricity use for the heat pumps: 3.0 GWh

Based on these data, models have been created for the BHPs according to the method presented in Chapter 2.6 Flexibility: Heat source shifting: District heat – Heat pump. The total maximum heat output for the BHPs is estimated to be 1.8 MW.

The building heat pumps are included as a heat source in all simulations of the archetype heat grids. The heat demand that they normally cover when operated as they currently are (non-flexible operation) is not included in the 500 GWh, which is the annual heat generation in the archetype heat grids.

3.3 BOREHOLE STORAGE CONNECTED TO BUILDINGS

This type of flexibility differs from the other two in that it does not exist in most DH grids. Instead, a possible borehole storage described in (Nilsson, et al., 2016) is simulated. This borehole storage is connected to a building whose heat demand for space heating is covered to 67% of heat from the borehole storage from October–

April. Table **8** shows the energy and power constraints used for the borehole in cases where it is controlled flexibly. Values that differ from those in the previous study are in bold text. The differences are that there is a period during spring and autumn when it is allowed to both charge and discharge the borehole storage. Also, a greater discharge power is allowed during autumn.

Table 8. Energy and power limitations for the borehole storage studied

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOT
Net heat transfer [MWh]													
DHgrid -> Storage					855	1350	1325	925	610				5065
Storage -> Building	407	377	386	291						287	361	370	2479
Max power [kW]													
DHgrid -> Storage				**2000**	2300	2000	2000	1600	1600	**1000**			
Storage -> Building	1500	1250	750	500	**250**				**1000**	**1500**	**1500**	1500	

3.4 COMPILATION OF SIMULATION CASES

Table 9 presents a summary of all simulation cases studied for all six archetype heat grids. There are two additional simulation cases on a variation of archetype heat grid: GHP and GHP S (Extra grid heat pump without/with storage tank) where 10% of the heat demand is allocated to a satellite area in the grid. These extra simulation cases are presented in Table **10**.

Table 9. Compilation of all simulation cases and description of how they differ from the reference case. All simulation cases are applied to all six archetype heat grids

Simulation case	**Description**
Reference case	Simulation case where the heat grid is simulated without any kind of demand flexibility being used. There is still some flexibility from storing heat in the distribution grid and, in three of the archetype heat grids, also in the hot water storage tank.
Thermal storage in buildings 20%	Simulation case where the 65 properties with the largest capacity for thermal storage are used as flexibility. These properties account for 20% of the annual heating demand in the heat grid.
Thermal storage in buildings 44%	Simulation case where the 287 properties with the largest capacity for thermal storage are used as flexibility. These properties account for 44% of the annual heating demand in the heat grid.
BHP flexible	Control of heat pumps in buildings is included in the heating grid optimization, and these pumps compete economically with all other heat sources for supplying heat every hour.
Borehole not flexible	Borehole storage is available, but its control is not linked to the heating grid optimization. This simulation should serve as an additional reference scenario for the borehole flexible case.
Borehole flexible	Borehole storage is available and its operation is optimized as a part of the heat grid optimization.
Combined flexibility	Three types of flexibility are combined in one simulation: thermal storage in buildings 20%, BHP flexible, and borehole flexible.

Table 10. Compilation of the simulation cases applied to a variation of an archetype heat grid: GHP and GHP S – 10% of heat demand in satellite grid

Simulation case	**Description**
Reference case	Simulation case where the heat grid is simulated without any kind of demand flexibility being used. There is still some flexibility from storing heat in the distribution grid and, in three of the archetype heat grids, also in the hot water storage tank.
Thermal storage in buildings 20% – All flexibility central	Simulation case where the 65 properties with the largest capacity for thermal storage are used as flexibility. These properties account for 20% of the annual heating demand in the heat grid. All properties utilized are located centrally in the heat grid.
Thermal storage in buildings 20% – Half the flexibility in the satellite	Simulation case where the 65 properties with the largest capacity for thermal storage are used as flexibility. These properties account for 20% of the annual heating demand in the heat grid. Half of the properties utilized are located in the satellite part of the grid.

4 The value of flexible heat demand

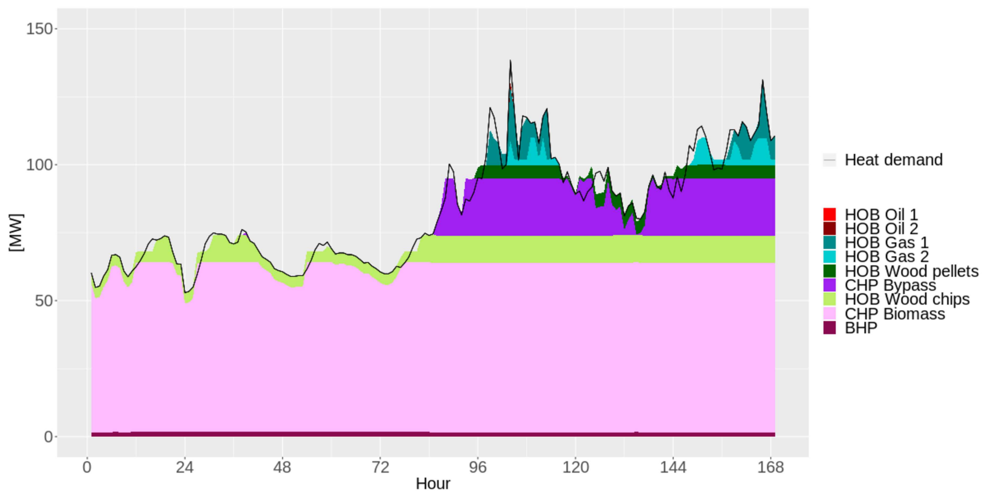
This chapter presents a selection of results from the simulation study. A number of key performance indicators have been analyzed for all simulation cases for all archetype heat grids. There is not enough room for presenting all the results in this format, but all key performance indicators are compiled in Appendix A for the reader who wants to dig deeper and scale or apply the results to other DH grids (using Table **6**).

4.1 THERMAL STORAGE IN BUILDINGS

The simulated heat grid optimization utilizes thermal storage in buildings in a manner quite similar to how a hot water storage tank is utilized. Economic and environmental value arise mainly due to two effects:

- Smoothing of heat load profile, which means that the use of expensive peak load HOBs can be replaced by cheaper base load units.
- Better optimization of CHP (and any heat pumps) against electricity prices. During periods when heat generation operational cost is strongly linked to electricity prices, the heat generation is shifted so that the CHP can generate maximum electricity during hours with high electricity prices (and heat pumps can use electricity when the prices are the lowest).

Both effects can be observed in



Energiforsk

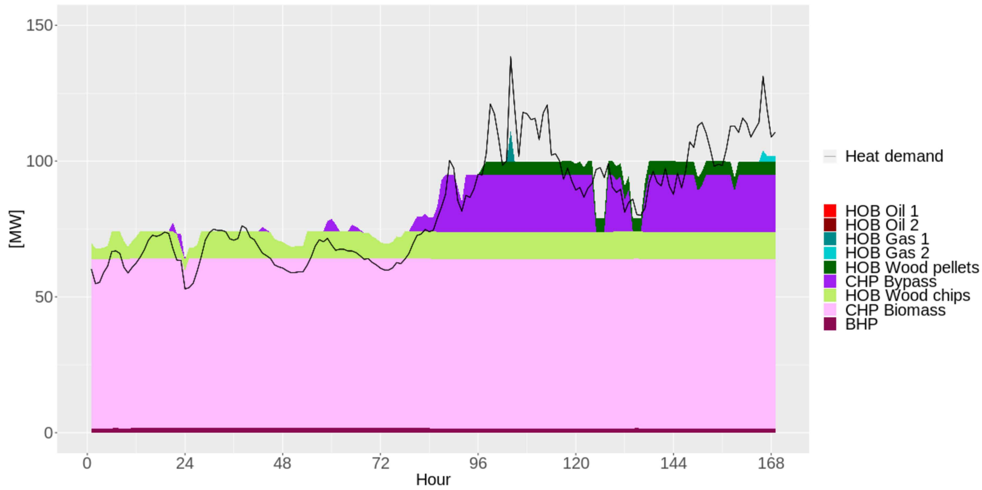
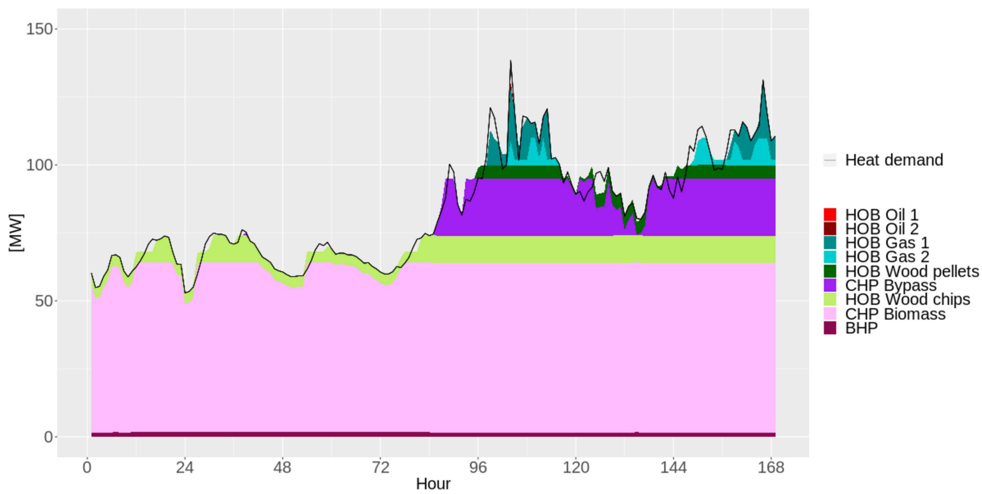


Figure 8, which compares heat generation for the reference case and a case where thermal storage in buildings is utilized for the CHP (extra combined heat and power without a hot water storage tank) archetype heat grid.

- Peak load (covered by gas HOBs) is greatly reduced and replaced primarily by HOBs with wood chips and wood pellets as fuel. There is also a slight increase in heat generation from CHP in normal operation (maximum electricity output).
- During the second half of the week, there is a need for the CHP unit to run in bypass operation (only heat generation and no electricity generation). With flexibility, it is possible to operate normally (with no bypass) on two occasions during the second half of the week and hence sell electricity during those hours. The thermal storage in buildings makes it possible for the optimization to do this during periods with the highest electricity prices.



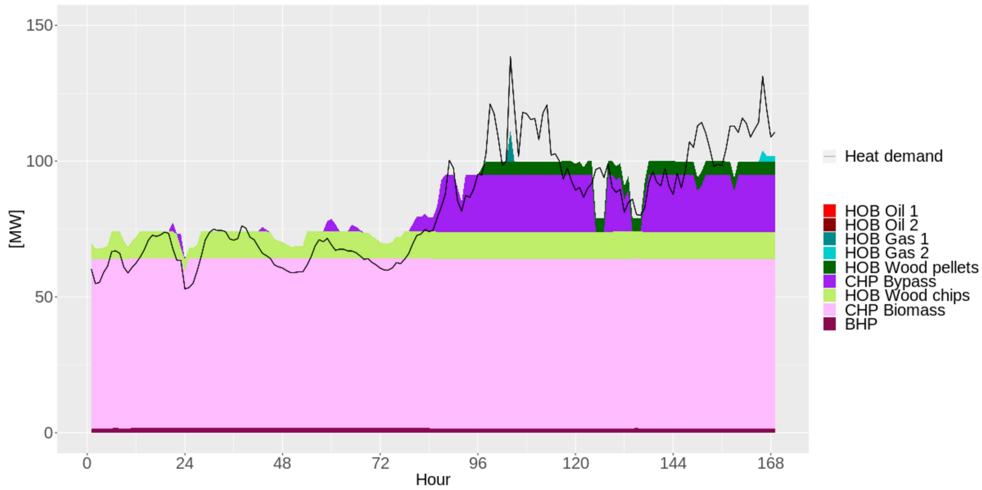
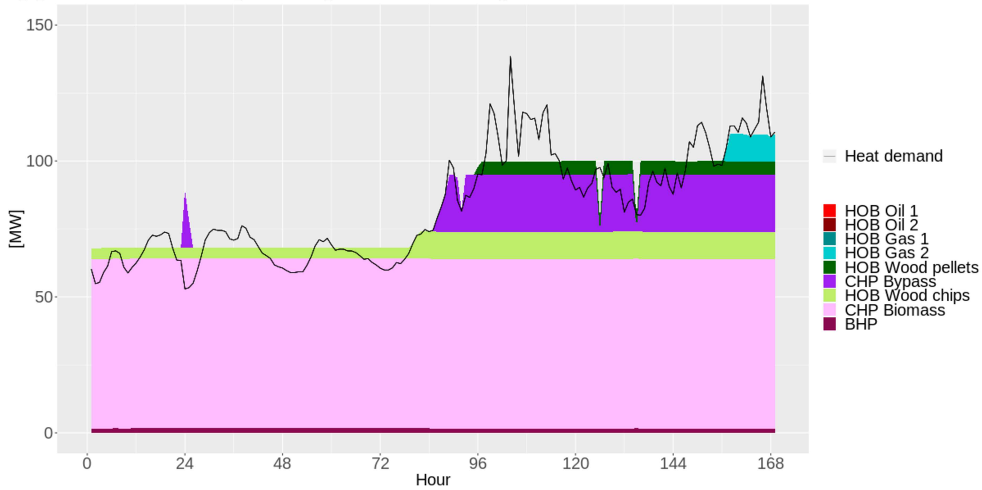


Figure 8. Heat generation during a November week in 2016 for archetype heat grid CHP

Upper figure: Reference case (no demand flexibility)

Lower figure: Thermal storage in buildings 44%

Even for DH grids that already have a hot water storage tank, there are opportunities to improve operation during the same week.



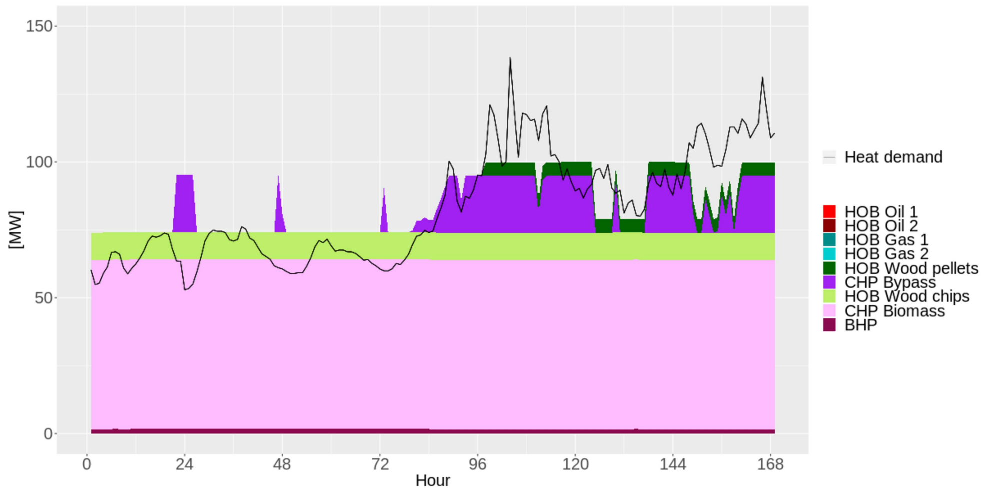
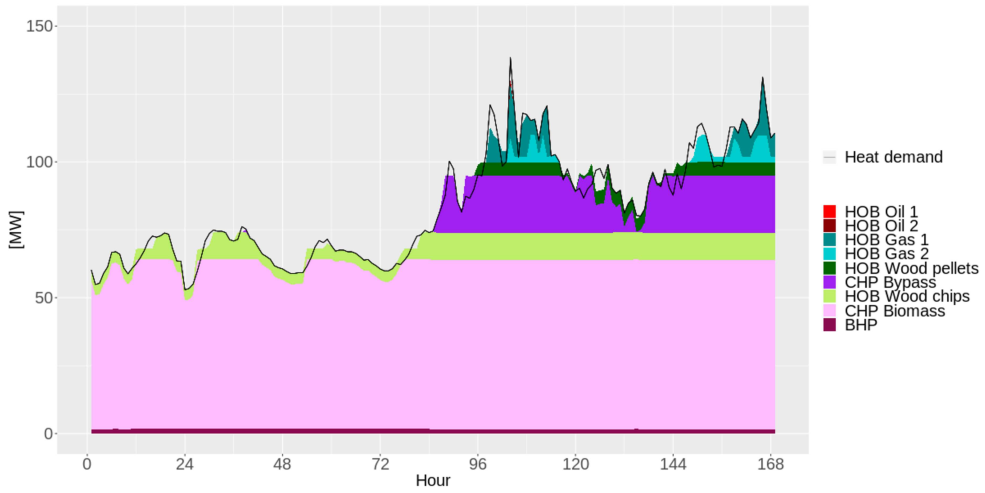


Figure 9 shows the same week for archetype heat grid with the same production mix as in



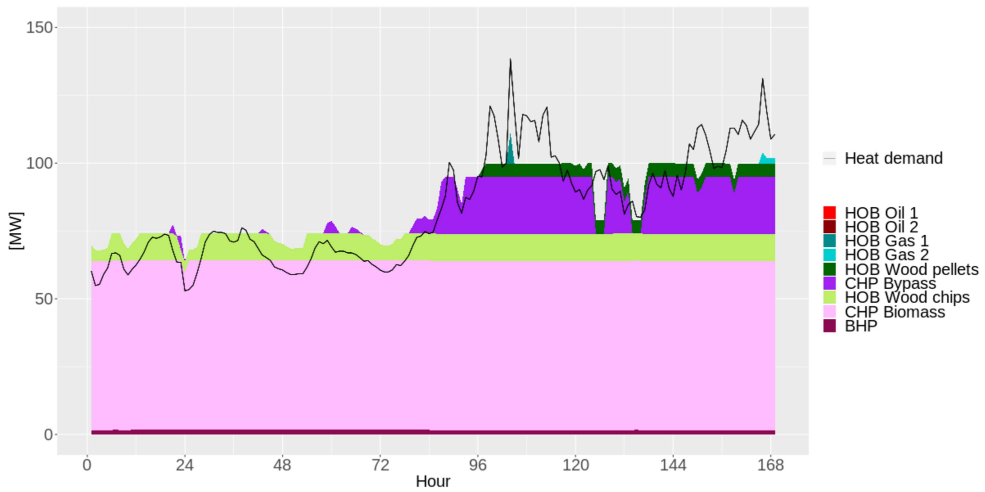
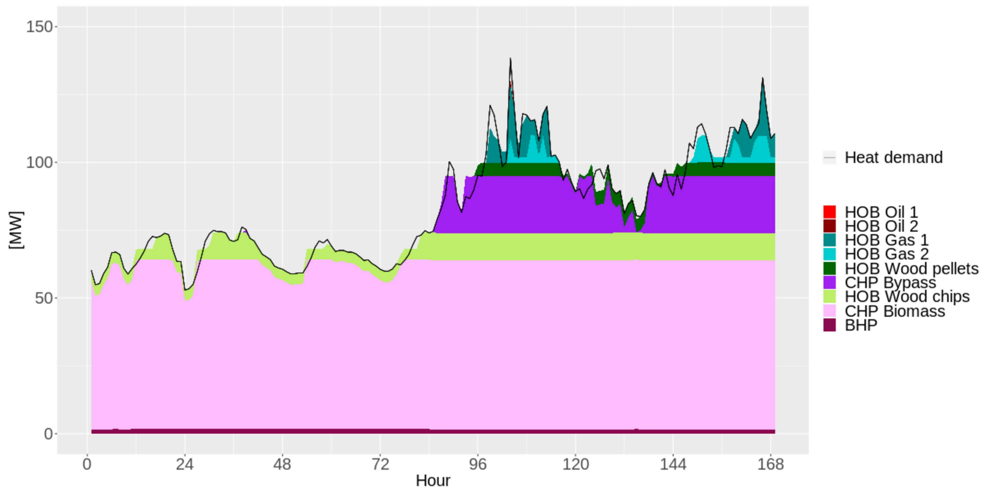


Figure 8 but with a hot water storage tank. Here we can see that the hot water storage tank has already contributed with similar benefits as those contributed by thermal storage in buildings in



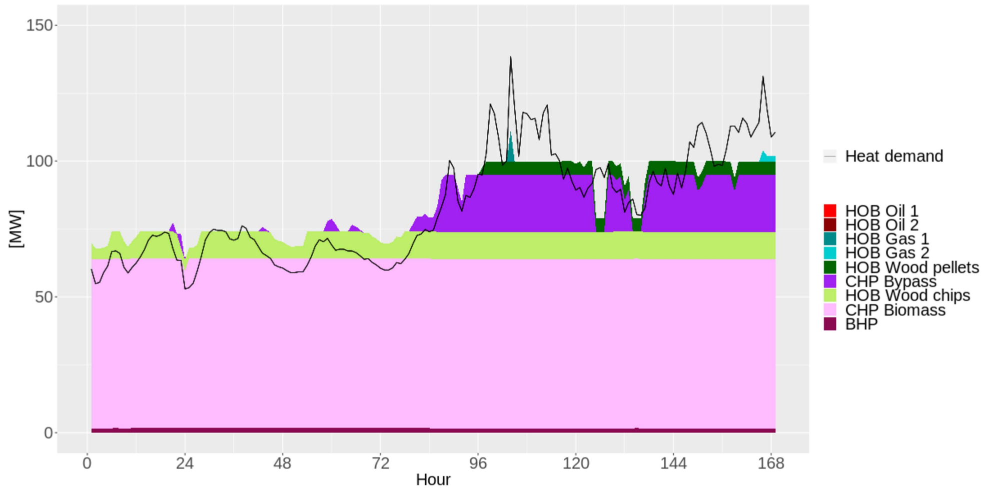


Figure 8 (fossil peak load has been greatly reduced and the hours of bypass operation in CHP unit have been adjusted slightly). If thermal storage in buildings is also added, then there are additional opportunities for optimization: there are two main additional advantages:

- Peak load gas HOBs are not required to start during the whole week. Instead, heat generation is increased from the wood chips HOB.

- CHP is optimized even more toward the electricity price. The hours when it goes into bypass operation are allocated to those hours with the lowest electricity prices. This also happens during selected hours with low electricity prices during the first half of the week to heat up buildings utilized as thermal storage extra, hence avoiding the use of gas HOBs during the second half of the week.

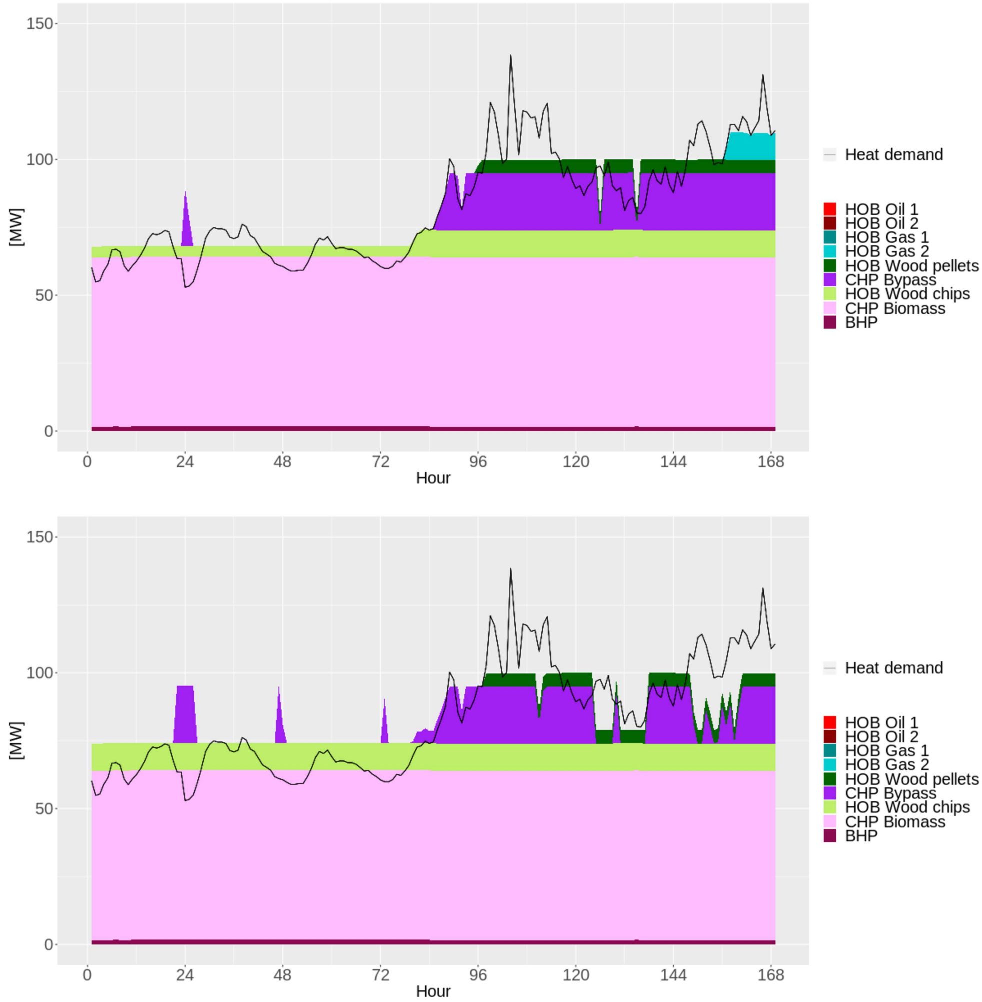
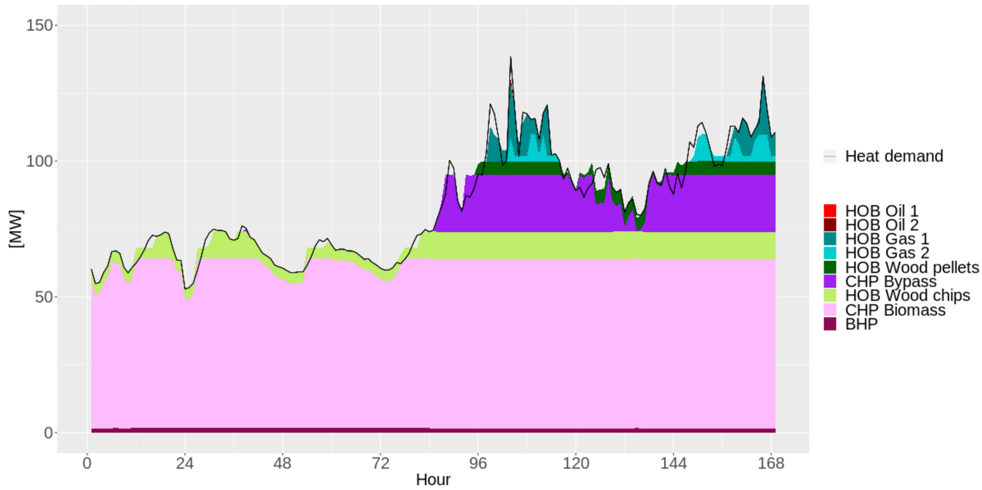


Figure 9. Heat generation during a November week in 2016 for archetype heat grid: CHP S
The difference from



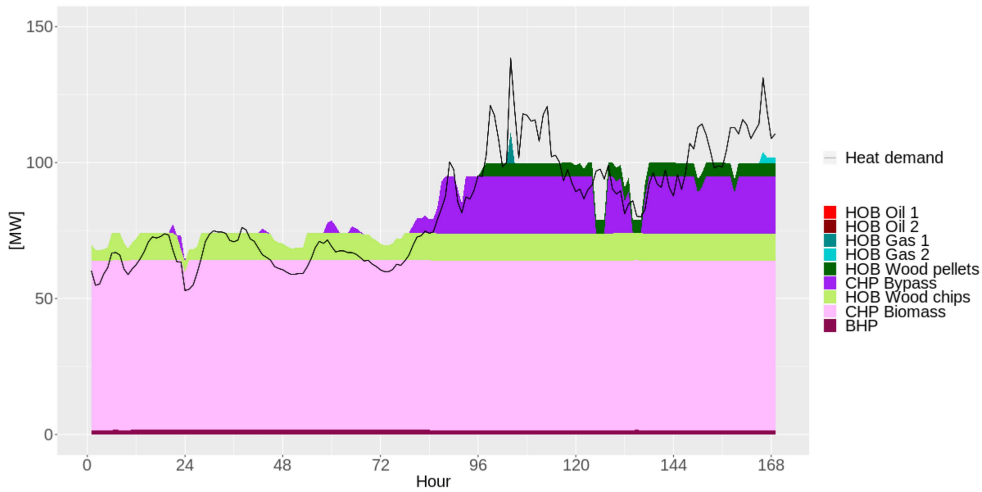


Figure 8 is that there is a hot water storage tank in the heat grid.

Upper figure: Reference case (no demand flexibility)

Lower figure: Thermal storage in buildings 44%.

Even during weeks when there is no need for peak generation in HOBs, flexibility still has value. Figure 10 shows an April week for archetype heat grid: GHP (extra grid heat pump without storage tank). During this week, GHPs are on the margin for about half of the hours. By utilizing thermal storage in buildings, the GHPs can be controlled so that they generate heat to a greater extent during hours with low electricity prices. This reduces the variable operating cost and should at the same time have a balancing effect on the electricity grid.

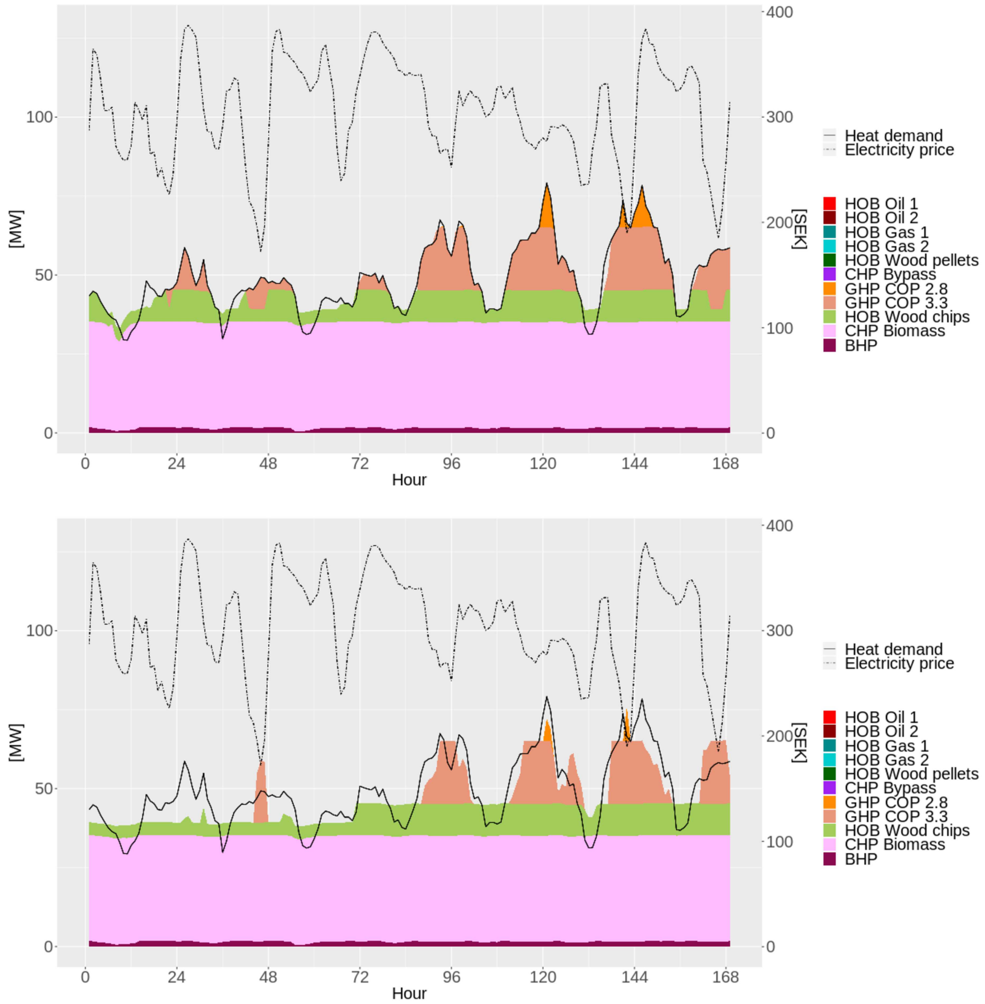


Figure 10. Heat generation during an April week in 2015 for archetype heat grid: GHP

Upper figure: Reference case (no demand flexibility)

Lower figure: Thermal storage in buildings 44%

Figure 11 shows the same week and simulation cases as Figure 10 but for type networks: EH (extra excess heat without storage tank). CHP is on the margin during parts of the week, and thermal storage in buildings enables shifting of CHP generation to hours with higher electricity prices. During the first half of the week, it is also possible for excess heat alone to fulfill the demand thanks to thermal storage in buildings.

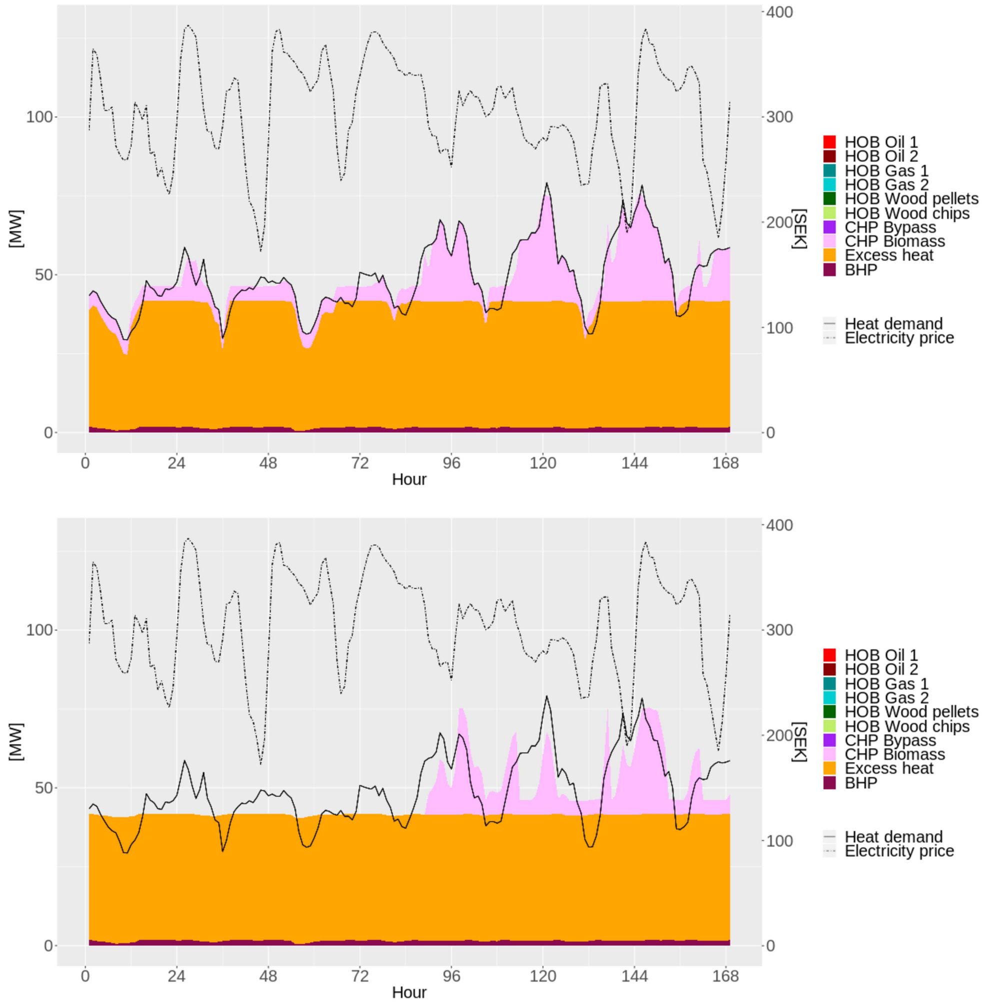


Figure 11. Heat generation during an April week in 2015 for archetype heat grid: EH
Upper figure: Reference case (no demand flexibility)
Lower figure: Thermal storage in buildings 44%

4.1.1 Impact on variable operational cost

The potential for reducing variable operating cost varies between the six studied archetype heat grids. As a reference key performance indicator, the average yearly variable operating cost for the simulation period (2015–2017) is used, see Table 11.

Table 11. Variable operational cost (average value for 2015–2017) for reference case (no demand flexibility)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	92.7 MSEK/yr	99.7 MSEK/yr
Extra grid heat pump (GHP)	104.6 MSEK/yr	109.1 MSEK/yr
Extra excess heat (EH)	42.4 MSEK/yr	47.0 MSEK/yr

When implementing thermal storage in buildings in 65 properties, corresponding to 20% of the annual heat demand, significant reductions in variable operating cost arise, as shown in Table **12**.

Table 12. Variable operating cost (average value for 2015–2017) for case: Thermal storage in buildings 20%. Absolute and relative reduction (in bold) of variable operating cost is relative to the reference case (without flexible demand)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	90.5 MSEK/yr **-2.1 MSEK/yr** **-2.3%**	95.7 MSEK/yr **-4.0 MSEK/yr** **-4.0%**
Extra grid heat pump (GHP)	102.7 MSEK/yr **-1.9 MSEK/yr** **-1.8%**	105.6 MSEK/yr **-3.5 MSEK/yr** **-3.2%**
Extra excess heat (EH)	40.6 MSEK/yr **-1.8 MSEK/yr** **-4.4%**	43.2 MSEK/yr **-3.8 MSEK/yr** **-8.1%**

In the archetype heat grids with hot water storage tanks, the decrease is 1.8–4.4%. In absolute terms, however, the decrease is about the same for all three archetype heat grids with hot water storage tanks, at 1.8–2.1 MSEK/yr. Approximately 1 MSEK/yr of this saving is caused by the reduced use of HOBs with oil or gas as fuel. Their operating cost decreases by 1.5 MSEK/yr for all heat grids and is replaced by alternative heat generation with a cost to the order of 0.5 MSEK/yr (it is not possible to say exactly what heat generation replaces the HOBs, and the estimate is based on a weighting of production cost for sources that are on the margin at intermediate levels of heat demand). The remaining saving come from optimizing the operation of CHP and/or GHPs against the electricity price, moving load between other heat sources, as well as a reduction of energy end usage in the buildings utilized (which we will return to in Table **14**). In the heat grids with extra combined heat and power generation (CHP and CHP S), the potential for optimization is the greatest in absolute terms, since CHP can benefit a lot from being optimized toward the electricity price. In the archetype heat grids with extra excess heat (EH and EH S), the reduction of variable operating cost is greatest, relatively speaking. This is because the variable operating cost is already very low, and the same reduction in absolute numbers has a greater impact if it is expressed relatively.

For archetype heat grids without a hot water storage tank, the reduction of variable operating cost is about twice as large as for archetype heat grids with a hot water storage tank, at 3.2–8.1% (compared to 1.8–4.4%). This is mainly due to the fact that thermal storage in buildings is used in a similar way as a storage tank in the optimization, and increasing amounts of flexibility have a decreasing value. If, for example, a hot water storage tank has sufficient capacity to completely eliminate the need for a peak load HOB, thermal storage in buildings does not add as much value during that demand peak. However, extra value can still be added, as exemplified in

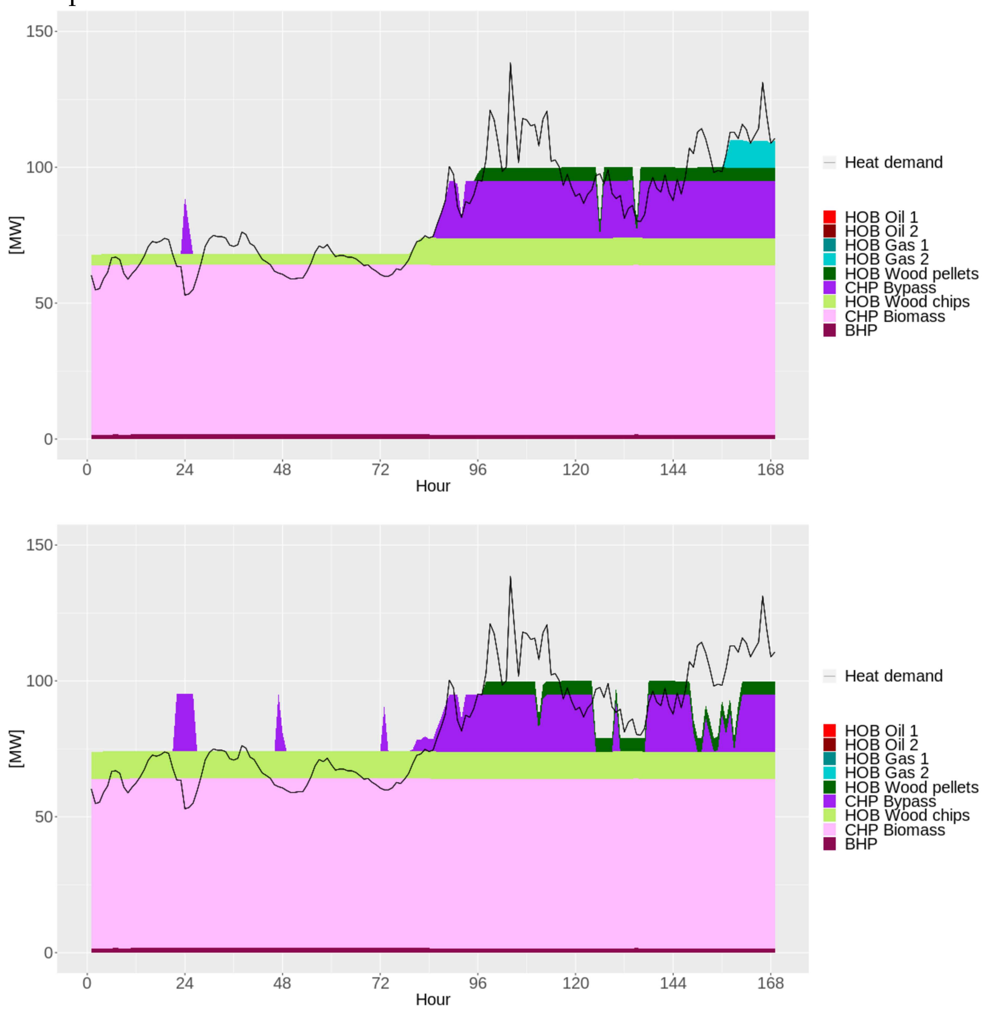


Figure 9. If a hot water storage tank is not available, thermal storage in buildings takes the "low hanging fruit" that is otherwise taken by the hot water storage tank, as exemplified in

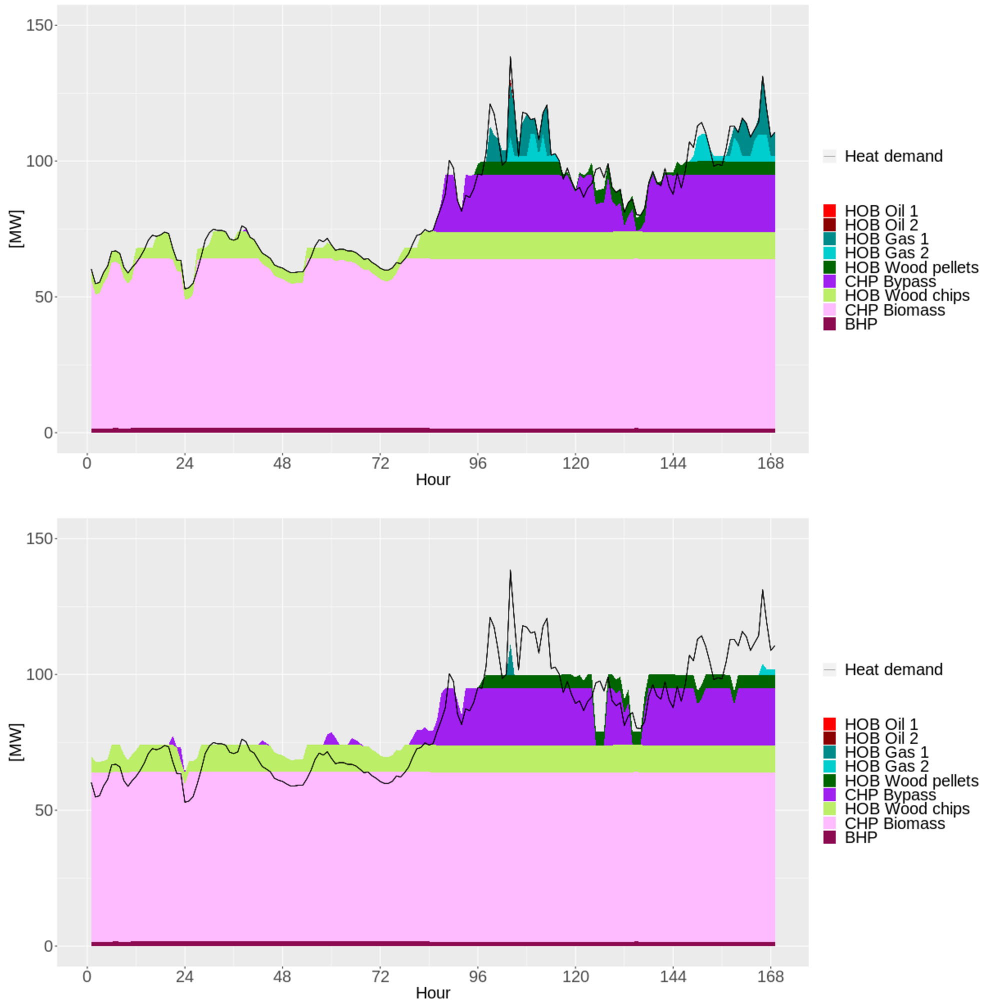


Figure 8. This explains the almost doubled reduction in variable operating cost in heat grids without a hot water storage tank.

If a significantly larger number of properties are utilized as thermal storage, as in the case of 287 properties corresponding to 44% of the annual heat demand (case: Thermal storage in buildings 44%), then an even greater reduction in variable operating cost is achieved (see Table **13**). In case: Thermal storage in buildings 20%, the decrease in variable operating cost measured in absolute terms is approximately the same for the three archetype heat grids with a hot water storage tank (3.6–3.9 MSEK/yr). The thermal storage in buildings 44% case has slightly more than double flexibility compared to the thermal storage in buildings 20% case, and the decrease in variable operating cost is slightly less than double. This indicates that there is a diminishing value of more flexibility, but the decline is not significant. However, a considerable number of properties are required to achieve the increased flexibility. As in the case of thermal storage in buildings 20%, the value of thermal storage in the 44% buildings case is significantly larger in heat grids without storage tanks, resulting in a 70–80% greater reduction in variable operating cost.

Table 13. Variable operating cost (average value for 2015–2017) for case: Thermal storage in buildings 44%. Absolute and relative reduction of variable operating cost is relative to case: Reference case (without flexible demand)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	88.7 MSEK/yr **-3.9 MSEK/yr** **-4.3%**	92.7 MSEK/yr **-7.0 MSEK/yr** **-7.1%**
Extra grid heat pump (GHP)	101.0 MSEK/yr **-3.6 MSEK/yr** **-3.5%**	103.0 MSEK/yr **-6.1 MSEK/yr** **-5.6%**
Extra excess heat (EH)	39.0 MSEK/yr **-3.8 MSEK/yr** **-8.0%**	40.6 MSEK/yr **-6.4 MSEK/yr** **-13.6%**

It is also important to keep in mind that the total heat use in the properties is affected when utilizing thermal storage in buildings. This is because the indoor temperature of the buildings is allowed to vary ±0.5°C compared to reference cases without thermal storage. The indoor temperature affects a property's heat losses, and the result of the optimization is that the average indoor temperature is somewhat lowered if flexibility is used and thus the heat load is also slightly lower. For case: Thermal storage in buildings 20%, the annual heat use decreases by 0.5%, and for case: Thermal storage in buildings 44%, the decrease is 1.0%. The difference is very small between the archetype heat grids, both with and without a hot water storage tank. If these values are compared to the relative reduction in variable operating cost, one can estimate how much of the reduction in variable operating cost is due to a reduction of energy for end use in the properties, as shown in Table **14**. This ratio is in the range of 6–29% and is the highest for heat grid: GHP S. This can be interpreted as 71–94% of the reduction in variable operating cost being due to the cost per generated MWh heat being reduced, and 6–29% of the reduction is due to a reduction in the number of MWh heat generated.

Table 14. Reduction of total heat energy generated divided by reduction of variable operating cost (average value for 2015–2017) for cases: Thermal storage in buildings 20% (20% case in table) and Thermal storage in buildings 44% (44% case in table). This is a measure of how much of the savings are caused by a reduction of energy end use

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	20% case: 22% 44% case: 23%	20% case: 13% 44% case: 14%
Extra grid heat pump (GHP)	20% case: 28% 44% case: 29%	20% case: 16% 44% case: 18%
Extra excess heat (EH)	20% case: 11% 44% case: 13%	20% case: 6% 44% case: 7%

If the reduction in variable operating cost is distributed over the properties that are utilized as thermal storage, a measure of the annual economic value per utilized property is obtained, as shown in Table 15. There is a large difference between the thermal storage in buildings 20% and 44% cases for all heat grids (by about a factor of 2.5). This is partly due to a reduced benefit from increasing the amount of flexibility if flexibility is already present, but the major cause is that the thermal storage in buildings 44% case needs to utilize considerably more properties (287, compared to 65 in the thermal storage in buildings 20% case) to achieve little more than a doubling of available flexibility. There is also a significant difference in the reduction of variable operating cost per utilized property between the archetype heat grids with a hot water storage tank and those without. This is a direct consequence of the fact that the value of thermal storage in buildings is about 70–100% higher in heat grids without a hot water storage tanks, as already shown in Table 12 and Table 13.

Table 15. Reduction of variable operational cost per utilized property (average value for 2015–2017) for cases: Thermal storage in buildings 20% (20% case in table) and Thermal storage in buildings 44% (44% case in table)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	20% case: 33 tSEK 44% case: 14 tSEK	20% case: 62 tSEK 44% case: 25 tSEK
Extra grid heat pump (GHP)	20% case: 29 tSEK 44% case: 13 tSEK	20% case: 53 tSEK 44% case: 21 tSEK
Extra excess heat (EH)	20% case: 28 tSEK 44% case: 12 tSEK	20% case: 59 tSEK 44% case: 22 tSEK

4.1.2 Environmental effects

Utilizing thermal storage in buildings affects the amount of heat generated from all heat sources and how much electricity is generated in CHP and used in heat pumps. All of these factors affect the emission of CO2e (carbon dioxide equivalents), both directly and indirectly, by increasing or decreasing alternative electricity generation. Reference values for CO2e for the six archetype heat grids for the reference case (without demand flexibility) are shown in Table **16**. The large impact on CO2e from generated and used electricity is linked to the use of the consequence perspective in this study, where extra generated electricity is mainly assumed to replace fossil electricity generation in the electricity grid. As a consequence, the CO2e values are lowest for heat grid: CHP S and highest for heat grid: GHP.

Table 16. CO2e emissions from a consequence perspective for reference case (without demand flexibility)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	Fuel use: 11.9 kton Sold el.: -67.2 kton **Tot: -55.3 kton**	Fuel use: 12.9 kton Sold el.: -65.2 kton **Tot: -52.3 kton**
Extra grid heat pump (GHP)	Fuel use: 8.9 kton Sold el.: -51.2 kton Bought el.: 42.1 kton **Tot: -0.3 kton**	Fuel use: 9.6 kton Sold el.: -50.1 kton Bought el.: 42.1 kton **Tot: 1.6 kton**
Extra excess heat (EH)	Fuel use: 5.9 kton Sold el.: -22.4 kton **Tot: -16.5 kton**	Fuel use: 6.8 kton Sold el.: -21.2 kton **Tot: -14.5 kton**

When utilizing thermal storage in buildings, the sum of direct and indirect CO2e emissions for all archetype heat grids decreases, as shown in Table **17**. For all heat grids, direct emissions from fuel use are reduced, which is largely due to a reduction in the use of fossil-fueled HOBs. Since the HOBs are the same for all the heat grids studied, this reduction is approximately the same for all heat grids without hot water storage tanks (24% for thermal storage in buildings 20% and 38% for thermal storage in buildings 44%) and also for all heat grids with hot water storage tanks (16% for thermal storage in buildings 20% and 26% for thermal storage in buildings 44%). Regarding indirect CO2e emissions (caused by bought and sold electricity), the results differ between the studied heat grids. This is because the optimization aims to minimize variable operating cost, and units that generate electricity (CHP) and use electricity (GHP), unlike heat only boilers (HOB) and excess heat, do not have the same ranking for variable operating cost and CO2e impact. CHP (when electricity is produced) gives rise to negative indirect CO2 emissions, which is lower than excess heat and which usually has a lower variable operating cost. Heat pumps have significantly higher indirect CO2e emissions than HOBs with wood chips or wood pellets as fuel, while GHPs have a lower variable operating cost. These factors mean that optimal operation from a CO2e perspective is not the same as optimal operation from an economic perspective. Overall, this is offset by a reduction in heat generation from fossil fuel HOBs, but it is not certain that this is the case in DH grids without fossil fuels covering the peak load. This is most likely due to whether there is a clear correlation between the parameter that is minimized in the optimization (in this case, variable operating cost) and direct/indirect CO2e emissions.

Table 17. Impact on CO2e emissions from a consequence perspective for case: Thermal storage in buildings 20% relative to reference case (without demand flexibility)

	With storage tank (S)	**Without storage tank**
Extra combined heat and power (CHP)	Fuel use: -0.5 kton Sold el.: -0.1 kton **Tot: -0.6 kton**	Fuel use: -0.8 kton Sold el.: -0.8 kton **Tot: -1.7 kton**
Extra grid heat pump (GHP)	Fuel use: -0.4 kton Sold el.: +0.2 kton Bought el.: -0.03 kton **Tot: -0.3 kton**	Fuel use: -0.8 kton Sold el.: -0.3 kton Bought el.: ±0.0 kton **Tot: -1.1 kton**
Extra excess heat (EH)	Fuel use: -0.4 kton Sold el.: -0.4 kton **Tot: -0.8 kton**	Fuel use: -0.8 kton Sold el.: -0.6 kton **Tot: -1.4 kton**

When the amount of available flexibility is more than doubled (case: Thermal storage in buildings 44%), the trends from case: Thermal storage in buildings 20% are enhanced. For all heat grids, the CO2e emissions from fuel use are reduced, as shown in Table **18**. Indirect CO2e emissions from bought and sold electricity are also reduced for all heat grids.

Table 18. Impact on CO2e emissions from a consequence perspective for case: Thermal storage in buildings 44% relative to reference case (without demand flexibility)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	Fuel use: -0.7 kton Sold el.: -0.3 kton **Tot: -1.1 kton**	Fuel use: -1.4 kton Sold el.: -1.3 kton **Tot: -2.7 kton**
Extra grid heat pump (GHP)	Fuel use: -0.7 kton Sold el.: +0.02 kton Bought el.: -0.3 kton **Tot: -0.9 kton**	Fuel use: -1.2 kton Sold el.: -0.5 kton Bought el.: -0.2 kton **Tot: -1.9 kton**
Extra excess heat (EH)	Fuel use: -0.7 kton Sold el.: -0.9 kton **Tot: -1.6 kton**	Fuel use: -1.2 kton Sold el.: -1.4 kton **Tot: -2.7 kton**

4.1.3 Balancing of the electrical grid

Although heat storage in buildings supplied by district heat does not have a direct connection to the electricity grid, the flexibility that it adds to the heat grid enables a more flexible operation of CHP units and GHP and thereby an opportunity to balance the electricity grid. The target function of the optimization is not to balance the electricity grid, but this should often be a consequence of an optimization that aims to minimize the total variable operating cost. If the average revenue for electricity sold from cogeneration increases due to thermal storage in buildings, this is an indicator that the thermal storage has a balancing effect on the electricity grid, even though the indicator is not a direct measure of the balance benefit achieved. This relationship also applies to the average price of purchased electricity used in GHP in the DH grid. Table **19** shows that for all archetype heat grids, the average revenue per MWh electricity sold increases if thermal storage in buildings is utilized. The increase is greatest for heat grid: CHP, which is natural since this is a heat grid with a lot of CHP and no hot water storage tank has taken away part of this potential. For the GHP and GHP S heat grids, the average cost per MWh of purchased electricity decreases, but not with the same magnitude.

Table 19. Average revenue from sold electricity and average cost of purchased electricity for reference case (without demand flexibility) and the change of these parameters for cases: Thermal storage in buildings 20% (20% case in table) and Thermal storage in buildings 44% (44% case in table) relative to reference case

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	**Reference case** Sold el.: 427 SEK/MWh **20% case** Sold el.: +2.3 SEK/MWh **44% case** Sold el.: +4.5 SEK/MWh	**Reference case** Sold el.: 411 SEK/MWh **20% case** Sold el.: +5.0 SEK/MWh **44% case** Sold el.: +10.5 SEK/MWh
Extra grid heat pump (GHP)	**Reference case** Sold el.: 417 SEK/MWh Bought el.: 808 SEK/MWh **20% case** Sold el.: +1.4 SEK/MWh Bought el.: -0.04 SEK/MWh **44% case** Sold el.: +2.7 SEK/MWh Bought el.: -0.3 SEK/MWh	**Reference case** Sold el.: 408 SEK/MWh Bought el.: 814 SEK/MWh **20% case** Sold el.: +3.8 SEK/MWh Bought el.: -2.1 SEK/MWh **44% case** Sold el.: +7.6 SEK/MWh Bought el.: -3.7 SEK/MWh
Extra excess heat (EH)	**Reference case** Sold el.: 433 SEK/MWh **20% case** Sold el.: +2.0 SEK/MWh **44% case** Sold el.: +3.7 SEK/MWh	**Reference case** Sold el.: 423 SEK/MWh **20% case** Sold el.: +4.4 SEK/MWh **44% case** Sold el.: +9.3 SEK/MWh

4.2 HEAT SOURCE SHIFTING: DISTRICT HEAT – HEAT PUMP

Today it is standard practice for there to be heat pumps in buildings (BHP) with DH, and heat pumps are always in operation as long as there is a heat demand that they can meet. This means that the reference case for the operating profile of the BHPs is the same for all six archetype heat grids, which is shown for one of the simulated years in Figure 12.

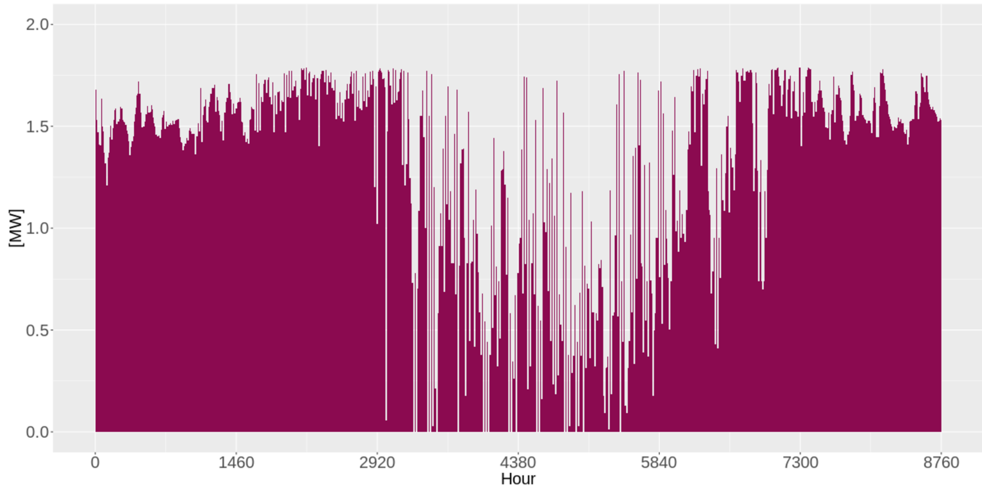


Figure 12. Total heat output from all 81 BHPs in 2017 for reference case (without flexible operation of BHPs or any other demand flexibility). The figure applies to all six archetype heat grids

When BHPs are treated as part of the total production optimization, they are switched off when the alternative cost for heat generation is lower in the DH grid, as shown for the heat grid: CHP S in Figure 13. If we compare with Figure 12, we see that on many occasions, when CHP is operating on the margin, all BHPs are shut down. Depending on the efficiency of the BHPs, they are also turned off on various other occasions. The BHPs with the highest efficiency are also in operation for many hours during the summer months when cogeneration is on the margin. During the summer, the BHPs also have the highest performance since the radiator temperature is low. When oil HOBs, gas HOBs, or bypass operation in CHP is on the margin, all BHPs are usually in operation.

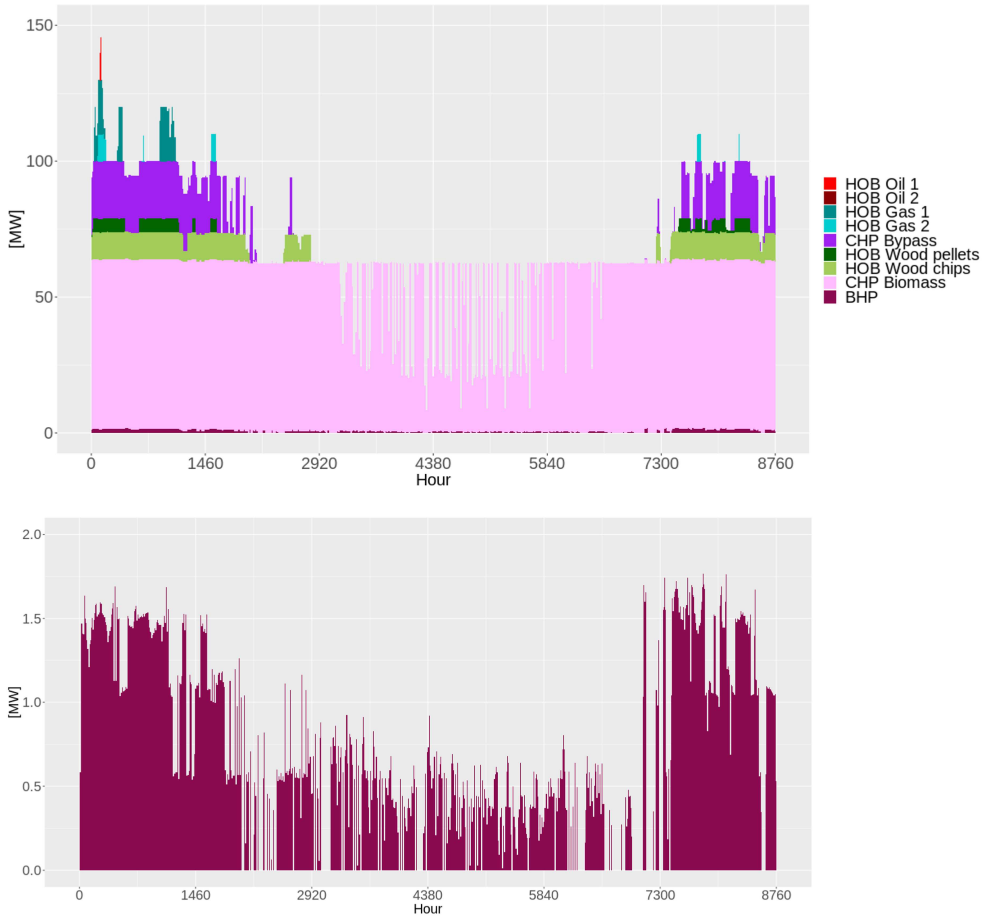
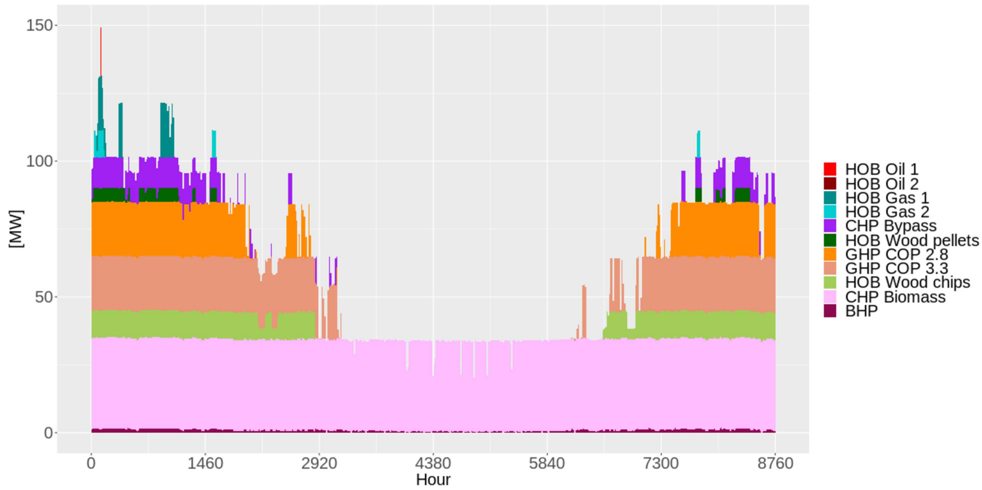


Figure 13. Upper figure: Heat generation from all heat sources in 2017 for case: BHP flexible. Heat grid: CHP S
Lower figure: Heat generation from BHPs has been lifted out to a separate figure to clarify its profile

In archetype heat grid: GHP S, the BHPs are controlled like the BHPs in heat grid CHP S for 4–5 months in the summer, because CHP with the same fuel is on the margin in both heat grids. The difference in operational pattern arises mainly during spring and autumn, when heat pumps in the heat grid (GHP) are on the margin. In these conditions, only BHPs with better performance than the GHPs in the heat grid are in operation.



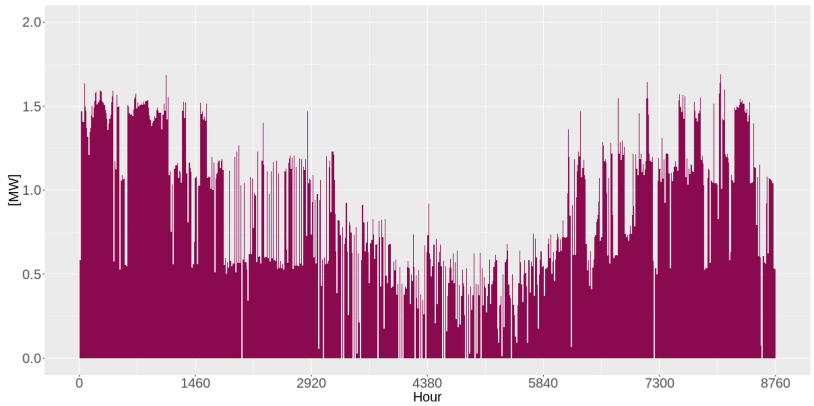
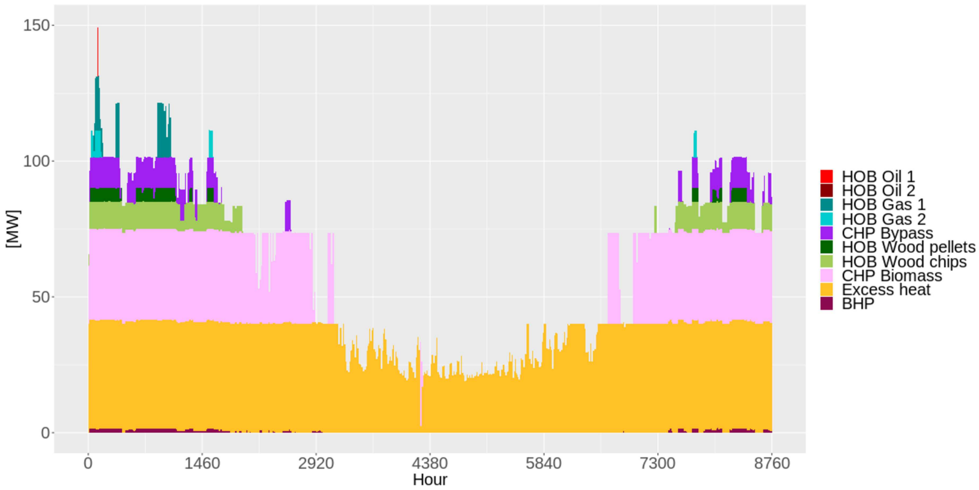


Figure 14. Upper figure: Heat generation for 2017 for case: BHP flexible. Archetype heat grid: GHP S

Lower figure: Heat generation from BHP has been lifted out to a separate figure to clarify its operational profile

There is a big difference in how flexibility in BHP control is utilized in archetype heat grid: EH S compared to the heat grids with other fuel mixes, as shown in Figure 15. All BHPs are completely shut down for 5–6 months when excess heat is on the margin. In order to achieve this control, no smart connected control of the heat pumps is needed, and a sufficiently low price for district heat during this period should have a similar effect (if building owners act on the price and turn off their heat pumps). During the winter, the operation of the BHPs is similar to that of the other heat grids, as most BHPs are turned off when normal operation of CHP is on the margin and turned on when HOBs or bypass in the CHP unit is on the margin.



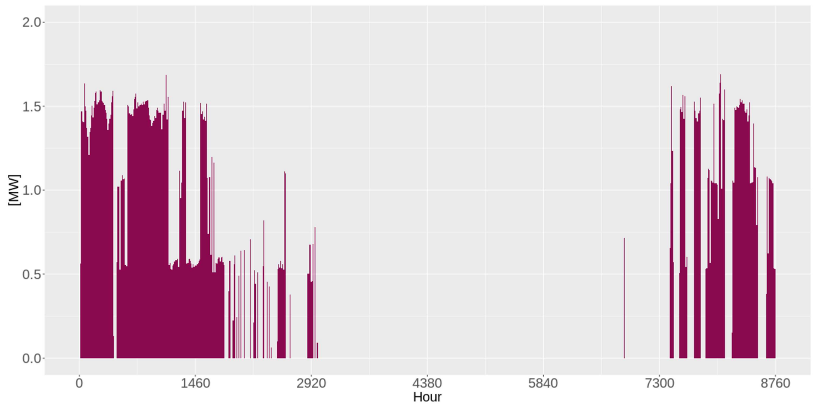


Figure 15. Upper figure: Heat generation during 2017 for case: BHP flexible. Archetype heat gird: EH S

Lower figure: Heat generation from BHP has been lifted out to a separate figure to clarify its operational profile

4.2.1 Impact on variable operational cost

Since the optimization target function is to minimize the combined variable operating cost for DH and BHPs, the total variable operating cost of both systems is studied. The variable operational cost for the reference case (no flexible operation of BHPs) is reported in Table **20**. The variable operating cost for BHPs is the same for all archetype heat grids because they have the same set of BHPs and they are controlled without regard to the DH grid.

Table 20. Variable operating cost (average value for 2015–2017) for district heating (DH) grids and for BHPs for reference case (BHPs are not flexibly controlled)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	DH: 92.7 MSEK/yr BHP: 2.9 MSEK/yr	DH: 99.7 MSEK/yr BHP: 2.9 MSEK/yr
Extra grid heat pump (GHP)	DH: 104.6 MSEK/yr BHP: 2.9 MSEK/yr	DH: 109.1 MSEK/yr BHP: 2.9 MSEK/yr
Extra excess heat (EH)	DH: 42.4 MSEK/yr BHP: 2.9 MSEK/yr	DH: 47.0 MSEK/yr BHP: 2.9 MSEK/yr

The potential for reducing total variable operating cost (district heating + heat pumps in buildings) varies greatly between archetype heat grids, as shown in Table **21**. The differences are small between heat grids with the same fuel mix with or without hot water storage tanks. The big difference depends on the fuel mix used. The largest decrease is for the EH and EH S heat grids, because excess heat is on the margin for a significant part of the year and then all BHPs are simply turned off. The total decrease of 1.11–1.12 MSEK/yr corresponds in that case to 38% of the BHPs variable operating cost in the case of normal (non-flexible) control (reference case). Part of this potential can be achieved through simpler methods such as a seasonal price for district heat, which encourages switching off BHPs during certain months. For the other heat grids, the reduction of combined (DH + BHP) variable operating cost is considerably greater for the CHP and CHP S heat grids compared to the GHP and GHP S heat grids. A strong contributing factor to this is likely that there is a much stronger correlation between marginal cost for heat pumps in buildings (BHPs) and district heat for the heat grids that utilize heat pumps (GHP and GHP S). This is because the marginal cost for all the heat pumps has a strong positive correlation with the electricity price. The opposite relationship applies to the CHP and CHP S heat grids, since the marginal cost for heat from cogeneration has a negative correlation with the electricity price (higher electricity price gives lower marginal cost for heat from CHP). The marginal cost for the two heating options in the buildings (CHP and BHP) thus correlates less with each other, and one option is often considerably more advantageous than the other, which makes flexible control of BHPs more valuable.

Table 21. Change in variable operating cost (average value for 2015–2017) for district heating (DH) grids and for BHPs for case: BHP flexible relative to reference case (BHPs are not flexibly controlled)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	DH: +0.77 MSEK/yr BHP: -1.39 MSEK/yr **TOT: -0.62 MSEK/yr**	DH: +0.73 MSEK/yr BHP: -1.42 MSEK/yr **TOT: -0.69 MSEK/yr**
Extra grid heat pump (GHP)	DH: +0.98 MSEK/yr BHP: -1.20 MSEK/yr **TOT: -0.22 MSEK/yr**	DH: +0.95 MSEK/yr BHP: -1.21 MSEK/yr **TOT: -0.26 MSEK/yr**
Extra excess heat (EH)	DH: +0.74 MSEK/yr BHP: -1.86 MSEK/yr **TOT: -1.12 MSEK/yr**	DH: +0.73 MSEK/yr BHP: -1.84 MSEK/yr **TOT: -1.11 MSEK/yr**

If the reduction of the combined variable operating cost in Table **21** is distributed among the BHPs that are utilized (81 in number), a measure of the cost saving per BHP is obtained, which is presented in Table **22**. The cost reduction ratio between the different heat grids is the same as in Table **21**. As an example, the economic potential for flexible control per building is about 8 tSEK per year for the heat grids with high share of heat from combined heat and power (archetype: CHP and CHP S).

Table 22. Reduction of total (DH + BHP) variable operating cost (average value for 2015–2017) divided by the number of buildings with a BHP

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	7.7 tSEK/yr	8.5 tSEK/yr
Extra grid heat pump (GHP)	2.7 tSEK/yr	3.2 tSEK/yr
Extra excess heat (EH)	13.8 tSEK/yr	13.6 tSEK/yr

If the economic potential for load shifting per BHP (Table **22**) is compared with thermal storage in buildings (Table **15**), then it is generally lower for each property utilized for load shifting from district heat to heat pump compared to thermal storage in buildings (2.7–13.8 tSEK/yr compared to 12–62 tSEK/yr). However, it should be pointed out that the cases for thermal storage in buildings consist of a selection of the 65 or 287 best suited properties, while the case load shifting from DH to BHP assumes that all properties with DH and BHPs are utilized. There are probably many small BHPs included that reduce the value per BHP. The maximum heat output per BHP has an average value of 22 kW, but there are many properties with considerably higher heat output. The economic potential of the flexibility can also be expressed as 120–610 tSEK per year and MW controllable heat output in BHPs.

4.2.2 Environmental effects

With the expanded system boundary, CO2e emissions from electricity use in BHPs are also included in the analysis. For the reference case (BHPs not controlled flexibly), BHPs get exactly the same load profile for all heat grids, which results in a CO2e emission of 2.6 kton/yr. This is added to the direct and indirect CO2e emissions from heat generation in the DH grids from Table **16**, and the result is presented below in Table **23**.

Table 23. Annual CO2e emissions from a consequence perspective for the reference case (BHPs are not flexibly controlled)

	With storage tank (S)	**Without storage tank**
Extra combined heat and power (CHP)	DH: -55.3 kton BHP: 2.6 kton TOT: -52.7 kton	DH: -52.3 kton BHP: 2.6 kton TOT: -49.7 kton
Extra grid heat pump (GHP)	DH: -0.3 kton BHP: 2.6 kton TOT: 2.3 kton	DH: 1.6 kton BHP: 2.6 kton TOT: 4.2 kton
Extra excess heat (EH)	DH: -16.5 kton BHP: 2.6 kton TOT: -13.9 kton	DH: -14.5 kton BHP: 2.6 kton TOT: -11.9 kton

The change (relative to the values in Table **23**) in CO2e emissions when BHPs are controlled flexibly is presented in Table **24**. For all archetype heat grids, the total CO2e emissions caused are reduced when BHPs are controlled flexibly. This is because CO2e emissions caused by heat pump's electricity use are greatly reduced, and the heat generation that replaces the reduced heat generation from BHPs is more favorable from a CO2e perspective. The heat generation that replaces heat from the BHPs varies between the different heat grids. For the CHP, CPS S, EH, and EH S heat grids, much of the heat is replaced by increased heat generation in the CHP unit, which also gives the DH grid reduced CO2e emissions (since the electricity generation is increased). The difference between heat grids with and without hot water storage tanks is almost non-existent.

Table 24. Change in annual CO2e emissions from a consequence perspective for case: BHP flexible relative to reference case (heat pumps are not flexibly controlled)

	With storage tank (S)	**Without storage tank**
Extra combined heat and power (CHP)	DH: -0.5 kton BHP: -1.3 kton TOT: -1.8 kton	DH: -0.5 kton BHP: -1.3 kton TOT: -1.8 kton
Extra grid heat pump (GHP)	DH: +0.6 kton BHP: -1.1 kton TOT: -0.5 kton	DH: +0.7 kton BHP: -1.1 kton TOT: -0.4 kton
Extra excess heat (EH)	DH: -0.6 kton BHP: -1.7 kton TOT: -2.3 kton	DH: -0.6 kton BHP: -1.7 kton TOT: -2.3 kton

4.2.3 Balancing of the electrical grid

Both electricity trading related to optimization in DH grids (generated by CHP and used GHPs) and electricity trading related to the electricity used in BHPs are affected by a co-optimization with flexible control of BHPs. Table **25** presents this data for the reference case (without flexible control of BHPs) and shows how the average price of bought and sold electricity is affected when BHPs are controlled flexibly. The average price for purchased electricity for heat pumps is significantly higher for BHPs than for GHPs because the electricity grid fee for BHPs is higher (220 SEK/MWh compared to 100 SEK/MWh).

Table 25. Average revenue from electricity sold and average cost of purchased electricity for reference case (BHPs are not flexibly controlled) and change of these parameters for case: BHP flexible relative to reference case

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	**Reference case** FV Sold el.: 427 SEK/MWh BHP Bought el.: 932 SEK/MWh **BHP flexible** FV Sold el.: +0.4 SEK/MWh BHP Bought el.: +9.8 SEK/MWh	**Reference case** FV Sold el.: 411 SEK/MWh BHP Bought el.: 932 SEK/MWh **BHP flexible** FV Sold el.: +0.4 SEK/MWh BHP Bought el.: +9.8 SEK/MWh
Extra grid heat pump (GHP)	**Reference case** FV Sold el.: 417 SEK/MWh FV Bought el.: 808 SEK/MWh BHP Bought el.: 932 SEK/MWh **BHP flexible** FV Sold el.: +0.2 SEK/MWh FV Bought el.: +0.2 SEK/MWh BHP Bought el.: +13.0 SEK/MWh	**Reference case** FV Sold el.: 408 SEK/MWh FV Bought el.: 814 SEK/MWh BHP Bought el.: 932 SEK/MWh **BHP flexible** FV Sold el.: +0.3 SEK/MWh FV Bought el.: -0.2 SEK/MWh BHP Bought el.: +16.3 SEK/MWh
Extra excess heat (EH)	**Reference case** FV Sold el.: 433 SEK/MWh BHP Bought el.: 932 SEK/MWh **BHP flexible** FV Sold el.: +0.4 SEK/MWh BHP Bought el.: +10.6 SEK/MWh	**Reference case** FV Sold el.: 423 SEK/MWh BHP Bought el.: 932 SEK/MWh **BHP flexible** FV Sold el.: +0.8 SEK/MWh BHP Bought el.: +14.8 SEK/MWh

For all archetype heat grids, the average price of bought electricity for BHPs increases when the heat pumps are controlled flexibly (by 9.8–16.3 SEK/MWh). BHPs are thus turned off more often when the electricity price is low than when the electricity price is high, which may seem strange, but there is a good explanation:

The marginal cost of heat generation in the DH grid varies much more than the marginal cost of operating heat pumps. In many circumstances, how the electricity price varies is of less importance than which heat source is operating on the margin in the DH grid. It is primarily when the marginal cost for heat generation in the DH grid is low that BHPs are turned off and, at the same time, the electricity price is also often low (but it never goes so low that the BHPs can compete with district heat under these conditions). This means that load switching between district heat and BHPs changes the operation of BHPs toward a more balanced role in both heat grids and the electricity grids, which is positive for the balance in the electricity grid.

Thanks to the flexible control of BHPs, however, the CHPs balancing effect on the electricity grid can be increased, albeit by relatively little (increased revenue for sold electricity: 0.2–0.8 SEK/MWh). One reason why this value changes less than the increased cost of the heat pump is that the BHPs only account for 2.1% of the network types' annual heat demand.

4.3 BOREHOLE STORAGE CONNECTED TO BUILDINGS

In the analysis of borehole storage connected to buildings, three cases have been compared.

• Reference case (no borehole bearing available)

• Borehole not flexible (borehole storage is available, but its control is not linked to the heating grid optimization)

• Borehole flexible (borehole storage is available and its operation is optimized as a part of the heat grid optimization)

Both cases in which borehole storage is available use the exact same design, described in Chapter 2.7 Flexibility: Borehole storage connected to buildings and 3.3 Borehole storage connected to buildings. The boreholes are charged with district heat, and the heat in the borehole can then be used directly without a heat pump to heat buildings. The only thing that distinguishes the two simulation cases is control of the borehole storage (that is, when the borehole is charged and discharged). Borehole flexible means that the extraction of heat can be allocated to hours and days when the heat sources with the highest marginal cost as are operating on the margin, which is exemplified for a November week in Figure 16. Since the discharging power of this borehole storage is only about of 1% of the heat grid's heat demand, it is difficult to determine the borehole effect solely through the upper figure. Therefore, the borehole discharging power is presented for the same time period in the lower figure. The sum of this power output (and charging and discharging of the distribution grid) is the difference between heat demand and generated heat in the upper figure. During the first half of the week, heat is used from the borehole only on two short occasions in order to have sufficient capacity during the second half of the week (which has higher marginal cost) to cover the entire heating demand in the buildings connected to the borehole storage.

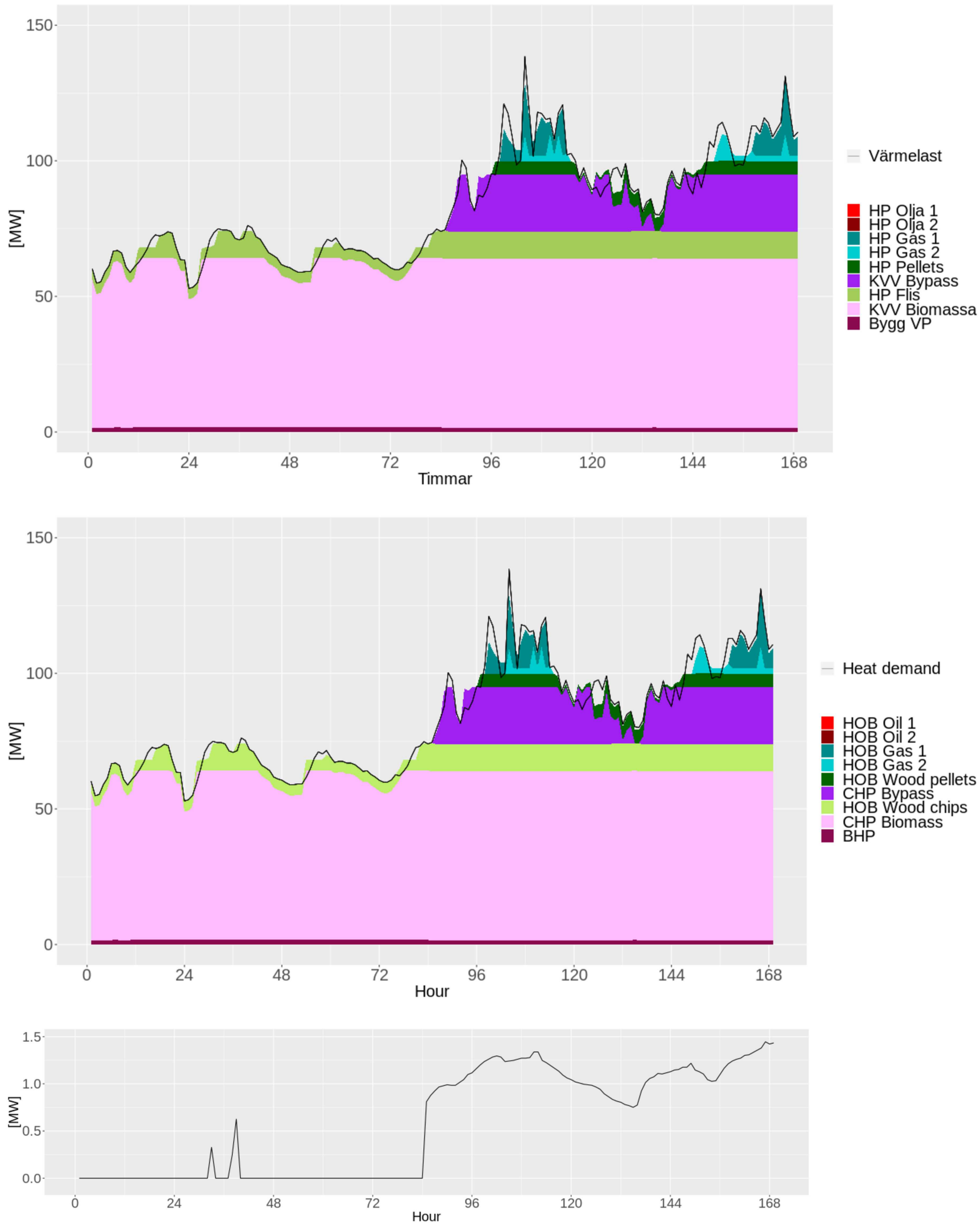


Figure 16. Upper figure: Heat generation from all heat sources during one week in November 2016 for case: Borehole flexible. Type network: CHP

Lower figure: Heat output from borehole storage during the same time period

An example of how the borehole storage is utilized during one week in March 2017 for archetype heat grid: EH is shown in Figure 17. This is an unusually cold week for March, and the borehole storage also has a lower temperature at the end of winter, which means that the maximum heating power it can deliver is not enough to meet the heat demand of the connected buildings. The borehole storage therefore delivers the maximum possible heating power during all hours except for a few hours when CHP is operating on the margin in the heat grid. During these hours, the building's entire heat demand is covered by district heat.

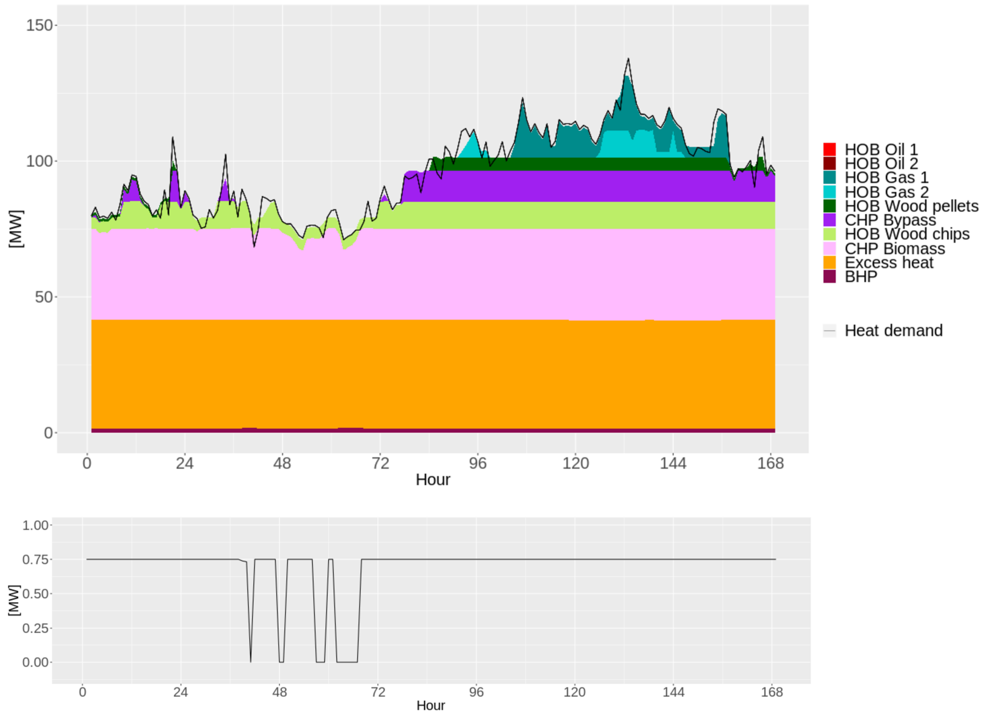


Figure 17. Upper figure: Heat generation from all heat sources for one week in March 2017 for case: Borehole flexible. Archetype heat grid: EH
Lower figure: Heat output from borehole storage during the same time period

4.3.1 Impact on variable operational cost

The variable operational cost in the borehole not flexible and borehole flexible cases in comparison to the reference case (without borehole storage) is shown in Table **11**. The reduction in variable operating cost for the non-flexible operation is 300–470 tSEK per year for the archetype heat grids: CHP, CHP S, GHP, and GHP S. For the heat grids EH and EH S, the borehole storage is considerably more valuable and the reduction of variable operating cost is 860–880 tSEK per year. This is because the basic premise for seasonal storage, a large difference in marginal cost for heat generation between summer and winter, is best fulfilled in these heat grids. For all archetype heat grids, flexible operation of the borehole storage gives a considerable increase in savings, in absolute terms 270–480 SEK per year and in relative numbers 36–133%. The increase in savings is greater in heat grids without hot water storage tanks, but the difference is not as significant as for thermal storage in buildings (presented in Table **13**). This is probably due to the fact that a seasonal storage fulfills another role in optimization than thermal storage in buildings, which works more like short-term storage, similar to a hot water storage tank.

Table 26. Change in variable operating cost (average value for 2015–2017) for the cases: Borehole not flexible (Not flex) and Borehole flexible (Flex) relative to reference case (without borehole storage)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	Not flex: -360 tSEK/yr Flex: -660 tSEK/yr Besparingsökning: 83%	Not flex: -300 tSEK/yr Flex: -700 tSEK/yr Besparingsökning: 133%
Extra grid heat pump (GHP)	Not flex: -330 tSEK/yr Flex: -600 tSEK/yr Besparingsökning: 82%	Not flex: -470 tSEK/yr Flex: -900 tSEK/yr Besparingsökning: 91%
Extra excess heat (EH)	Not flex: -860 tSEK/yr Flex: -1170 tSEK/yr Besparingsökning: 36%	Not flex: -880 tSEK/yr Flex: -1360 tSEK/yr Besparingsökning: 55%

4.3.2 Environmental effects

The sum of direct and indirect CO2e emissions has been calculated for the borehole flexible and borehole not flexible cases relative to the reference case (without borehole) and is presented in Table **27**. It may seem counterintuitive that archetype heat grids EH and EH S have the least environmental benefit of seasonal storage given that they have the opportunity to store excess heat from summer to winter. This is because, in the other heat grids, heat from CHP is mainly stored in the borehole, which has negative indirect CO2e emissions compared to excess heat, where CO2e emissions have been set to zero. The increased environmental gain through flexible control of the borehole storage is positive for all type of grids (3.1–29.0%) but is considerably less than the increased economic savings presented in Table **26** (36–133%). This is partly because heat sources that use or generate electricity have a variable operating cost that varies over time, but their CO2e emissions are assumed to be constant. Thus, the economic benefit arises by charging the borehole layer with heat from CHP for one hour with high electricity prices; environmentally, however, the CO2e impact is as great as if it is charged for one hour with lower electricity prices.

Table 27. Impact on CO2e emissions from a system perspective for the cases: Borehole not flexible (Not flex) and Borehole flexible (Flex) relative to reference case (without borehole storage)

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	Not flex: -1.97 kton/yr Flex: -2.03 kton/yr Ökning: 3.1%	Not flex: -1.89 kton/yr Flex: -2.03 kton/yr Ökning: 7.3%
Extra grid heat pump (GHP)	Not flex: -1.66 kton/yr Flex: -1.96 kton/yr Ökning: 17.8%	Not flex: -1.58 kton/yr Flex: -2.04 kton/yr Ökning: 29.0%
Extra excess heat (EH)	Not flex: -0.46 kton/yr Flex: -0.55 kton/yr Ökning: 19.8%	Not flex: -0.42 kton/yr Flex: -0.46 kton/yr Ökning: 10.7%

4.3.3 Balancing of the electrical grid

The change in revenue per MWh of electricity sold and cost per MWh of electricity purchased for the borehole not flexible and borehole flexible cases relative to the reference case (without borehole storage) is presented in Table **28**. For the archetype heat grids CHP, CHP S, GHP, and GHP S, the average revenue per MWh of electricity sold is reduced for the borehole not flexible case relative to the reference case. This is probably because CHP is on the margin in these types of networks during the summer months, when the borehole storage is being charged. This mainly means that more electricity is generated from CHP during the summer months and, because the electricity price is relatively low during this period, the average revenue is reduced. This is not true for heat grids EH and EH S, where excess heat is on the margin during the summer. Whether or not there is a hot water storage tank in the heat grid has little effect on the results.

Table 28. Average revenue from sold electricity and average cost of bought electricity for reference case (without borehole storage) and change of these parameters for the cases: Borehole not flexible and Borehole flexible relative to the reference case

	With storage tank (S)	Without storage tank
Extra combined heat and power (CHP)	**Reference case (without borehole)** Sold el.: 427 SEK/MWh **Borehole not flex** Sold el.: -1.1 SEK/MWh **Borehole flex** Sold el.: -0.5 SEK/MWh	**Reference case (without borehole)** Sold el.: 411 SEK/MWh **Borehole not flex** Sold el.: -0.9 SEK/MWh **Borehole flex** Sold el.: -0.3 SEK/MWh
Extra grid heat pump (GHP)	**Reference case (without borehole)** Sold el.: 417 SEK/MWh Bought el.: 808 SEK/MWh **Borehole not flex** Sold el.: -1.4 SEK/MWh Bought el.: -0.7 SEK/MWh **Borehole flex** Sold el.: -1.4 SEK/MWh Bought el.: -0.7 SEK/MWh	**Reference case (without borehole)** Sold el.: 417 SEK/MWh Bought el.: 808 SEK/MWh **Borehole not flex** Sold el.: -0.6 SEK/MWh Bought el.: -0.9 SEK/MWh **Borehole flex** Sold el.: -0.6 SEK/MWh Bought el.: -0.7 SEK/MWh
Extra excess heat (EH)	**Reference case (without borehole)** Sold el.: 433 SEK/MWh **Borehole not flex** Sold el.: +0.3 SEK/MWh **Borehole flex** Sold el.: +1.1 SEK/MWh	**Reference case (without borehole)** Sold el.: 423 SEK/MWh **Borehole not flex** Sold el.: -0.2 SEK/MWh **Borehole flex** Sold el.: +0.2 SEK/MWh

If the borehole storage is controlled flexibly, a significant part of the reduced revenue per MWh electricity sold that arises due to the existence of a borehole storage not that is not flexibly controlled is compensated for the CHP and CHP S heat grids. For the GHP and GHP S heat grids, the difference between flexible and not flexible control of borehole storage is very small, and this also applies to the purchased electricity for the grid heat pumps. In this case, flexible control of the borehole storage does not entail balancing of the electricity grid, which was the cause for thermal storage in buildings for the same heat grids according to Table **19**. Why this is so has not been investigated further, but it is likely connected to the fact that the borehole storage is a seasonal store, unlike the thermal storage in buildings, which primarily store heat on a daily or weekly basis. The heat grids: EH, EH S, CHP and CHP S increase their average revenue from sold electricity if the borehole storage is controlled flexibly (relative to the case with a borehole storage that is not controlled flexibly).

4.4 COMBINED FLEXIBILITY

Three types of flexibility have been evaluated individually, but one research question also concerns whether it is worth investing in several types of flexibility. Although these types of flexibility are profitable separately, it is not certain that they are as profitable if they are combined. The individual impact of three individual flexibility cases on a number of indicators is compared with simulation cases where the same types of flexibility are used together in each simulation. The results for variable operating cost are presented in Table 29.

Table 29. Total reduction of variable operating cost relative to the reference case summarized for three individual cases (Thermal storage in buildings 20%, Building HP flexible, Borehole flexible) and for case: Combined flexibility, where simulation is performed with the same three flexibilities together

	With storage tank (S)	**Without storage tank**
Extra combined heat and power (CHP)	**Sum: Individual flex** DH + BHP: -3.4 MSEK/yr **Combined flex** DH + BHP: -3.3 MSEK/yr **-2.6%**	**Sum: Individual flex** DH + BHP: -5.4 MSEK/yr **Combined flex** DH + BHP: -5.3 MSEK/yr **-2.1%**
Extra grid heat pump (GHP)	**Sum: Individual flex** DH + BHP: -2.7 MSEK/yr **Combined flex** DH + BHP: -2.7 MSEK/yr **-0.8%**	**Sum: Individual flex** DH + BHP: -4.6 MSEK/yr **Combined flex** DH + BHP: -4.5 MSEK/yr **-2.8%**
Extra excess heat (EH)	**Sum: Individual flex** DH + BHP: -4.1 MSEK/yr **Combined flex** DH + BHP: -4.0 MSEK/yr **-2.3%**	**Sum: Individual flex** DH + BHP: -6.3 MSEK/yr **Combined flex** DH + BHP: -6.1 MSEK/yr **-2.5%**

From Table **29** it can be seen that there is minimal conflict between the three types of flexibility for all network types. At most, the reduction in the variable operating cost is brought down by 2.8% if all three types of flexibility are used simultaneously, compared to if their reduction is added up from their individual simulations. This shows clearly that thermal storage in buildings, heat source shifting district heat – heat pump and flexible control of borehole storage carry out three different functions in optimizing heat generation in heat grids. If we also regard the hot water storage tank as a flexibility, then there is a "conflict" between thermal storage in buildings and a hot water storage tank, and the value of investing in one of these technologies is less if the other is already present in the system. This has already been explored in 4.1 Thermal storage in buildings.

The condition that the combined saving is (almost) equal to the individual saving when combining different types of flexibility applies not only to economic benefit: it is also true for a reduction in CO2e emissions, as shown in Table **30**.

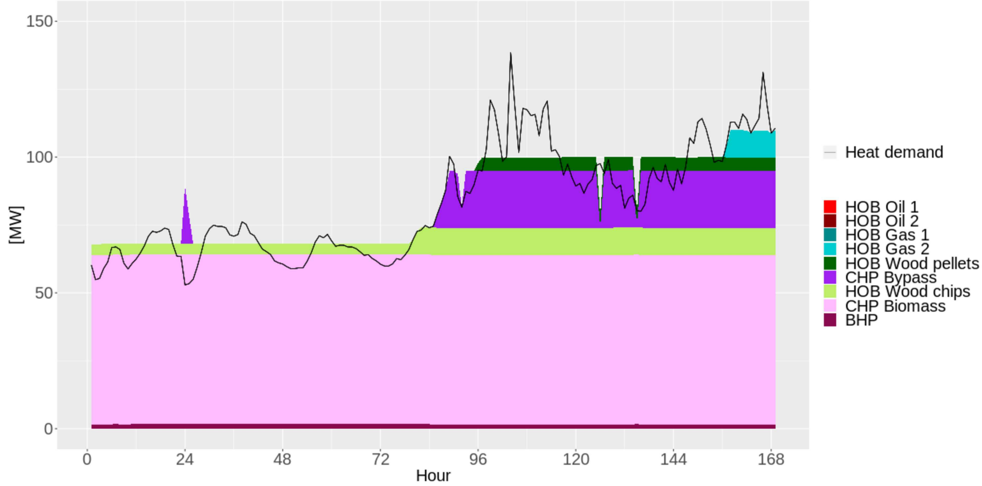
Table 30. Total reduction of CO2e emissions relative to the reference case summarized for three individual cases (Thermal storage in buildings 20%, Building HP flexible, Borehole flexible) and for case: Combined flexibility, where simulation is performed with the same three flexibilities together

	With storage tank (S)	**Without storage tank**
Extra combined heat and power (CHP)	**Sum: Individual flex** DH + BHP: -4.4 kton/yr **Combined flex** DH + BHP: -4.5 kton/yr **+2.8%**	**Sum: Individual flex** DH + BHP: -5.5 kton/yr **Combined flex** DH + BHP: -5.6 kton/yr **+0.4%**
Extra grid heat pump (GHP)	**Sum: Individual flex** DH + BHP: -2.8 kton/yr **Combined flex** DH + BHP: -2.9 kton/yr **+6.2%**	**Sum: Individual flex** DH + BHP: -3.6 kton/yr **Combined flex** DH + BHP: -3.6 kton/yr **+0.02%**
Extra excess heat (EH)	**Sum: Individual flex** DH + BHP: -3.7 kton/yr **Combined flex** DH + BHP: -3.6 kton/yr **-0.3%**	**Sum: Individual flex** DH + BHP: -4.2 kton/yr **Combined flex** DH + BHP: -4.3 kton/yr **+2.9%**

4.5 MANAGING TRANSMISSION BOTTLENECKS

When there is a region in a DH grid where the heating requirement is greater than the transmission capacity from other parts of the grid, the consequence is a need for local heat generation to fulfill the heat demand (if it is not more attractive to build a pumping station or increase the dimension of transmission pipes). In the example studied here, an area called a "satellite" is assumed to account for 10% of the heat demand in the grid and there is a transmission capacity of 8.5 MW. One of the HOBs with oil as fuel from the previous simulations has been moved to the satellite to cope with the heat supply.

Figure 18 shows an example week for an archetype heat grid (GHP S) with a hot water storage tank. Even though there is enough storage capacity to remove all use of the HOB with oil as fuel (as shown in



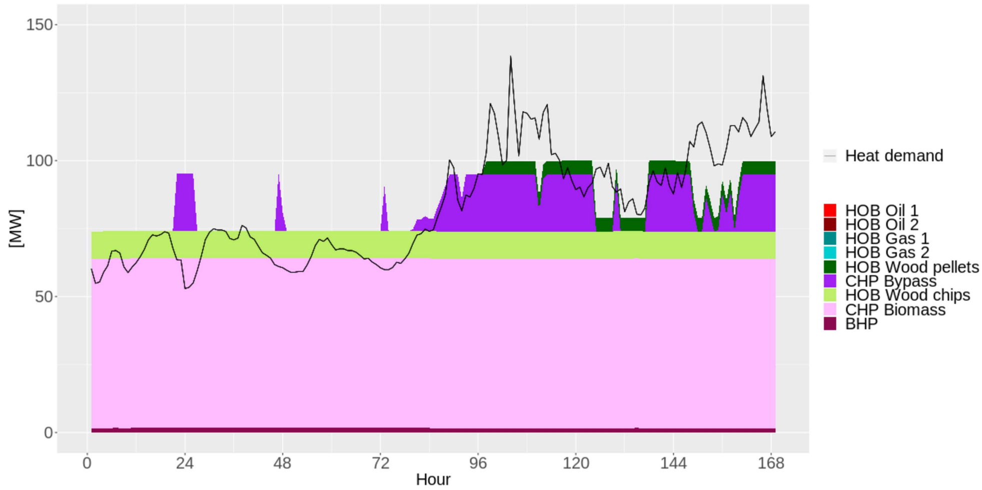


Figure 9), it is not possible to do so because the hot water storage tank is centrally located in the grid. Since there is a bottleneck in the system, it is necessary to use the hot water boiler with oil as fuel to cope with the heat supply in the satellite.

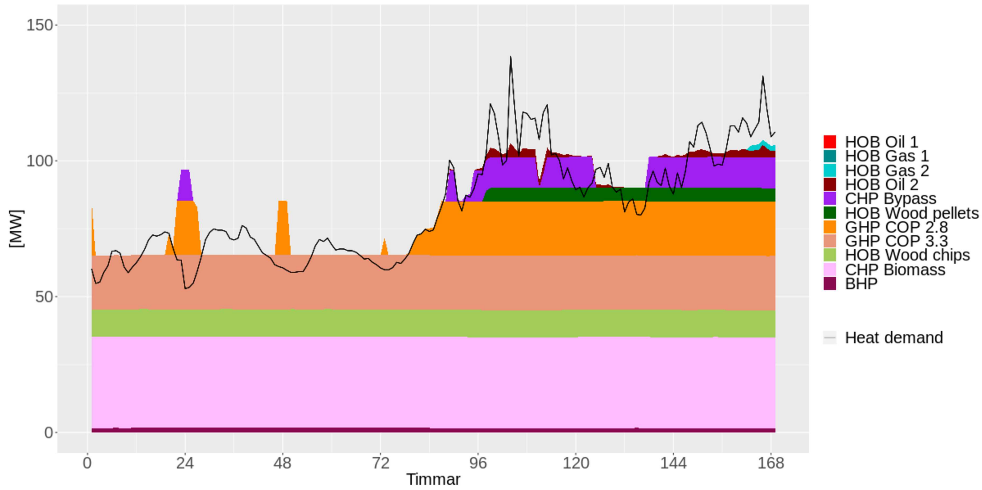


Figure 18. Heat generation during a November week for heat grid: GHP S with 10% of the heat demand in a satellite. Reference case without flexibility

If thermal storage in buildings is also utilized, it can be of great importance where in the heat grid the utilized buildings are located when calculating how much they can contribute to reduce peak load. Figure 19 shows the same example week as Figure 18 but with thermal storage in buildings corresponding to 20% of the heat demand. In this case, all the buildings utilized are located centrally in the heat grid. Although there is increased storage capacity, the amount of heat from the HOB with oil as fuel is not reduced. Instead, the flexibility is used to optimize CHP and GHPs against the electricity price.

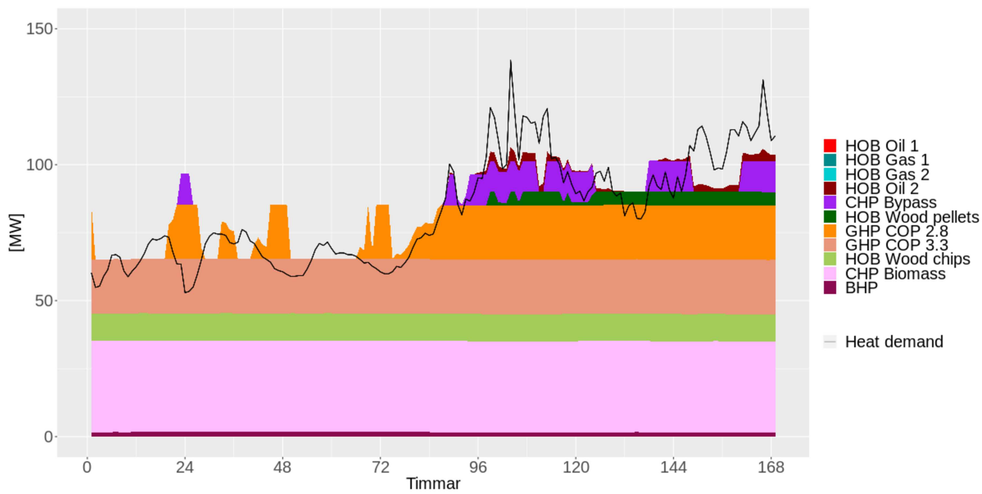


Figure 19. Heat generation during a November week for heat grid: GHP S with 10% of the heat demand in a satellite. Case: Thermal storage in buildings 20% – all flexibility central.

If half of the buildings utilized for thermal storage are instead located in the satellite, it is possible to avoid heat generation production in the HOB with oil as fuel, as shown in Figure 20.

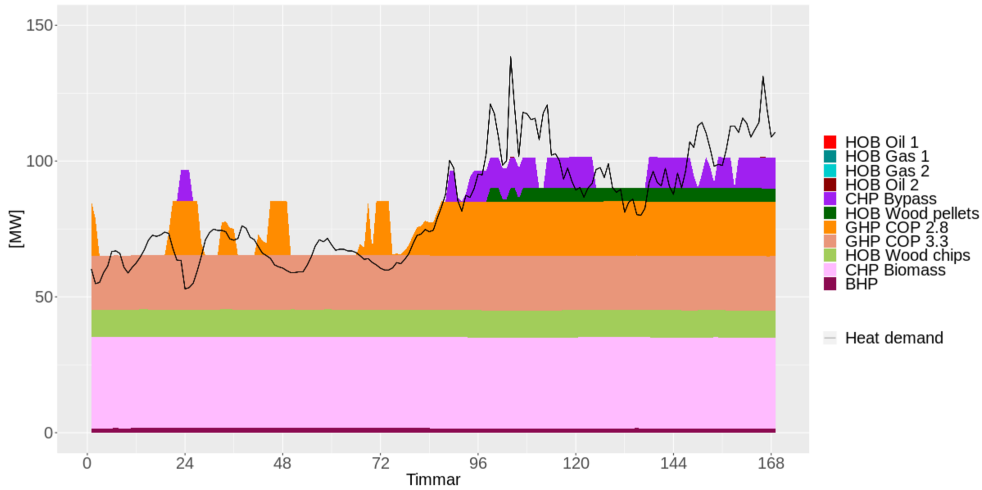


Figure 20. Heat generation during a sample week for heat grid: GHP S with 10% of the heat demand in a satellite. Case: Thermal storage in buildings 20% – half the flexibility in satellite

The variable operating cost is calculated for the archetype heat grids GHP and GHP S with 10% of the heat demand in a satellite. The reduction of variable operational cost by introducing thermal storage in buildings is compared to the same reduction for grids GHP and GHP S without a satellite (that was presented in Table **12**). This comparison is presented in Table **31**, which shows that the variable operating cost is 2.1 MSEK/yr (106.7–104.6) higher for heat grid GHP S and 1.7 MSEK/yr (110.8–109.1) higher for heat grid GHP. This is to be expected because the limited transmission capacity forces the operation of more expensive heat generation even though there is free capacity in cheaper heat generation centrally in the grid. With these values as a starting point, the variable operating cost is reduced by utilizing thermal storage in buildings. If all flexibility is allocated centrally in the network, the reduction is somewhat less for heat grids with satellites compared to heat grids without satellites. This is because there is one heat source less (the HOB in the satellite) that can benefit from the flexibility. If half of the buildings utilized as thermal storage are located in the satellite (this corresponds to all buildings in the satellite), a significantly greater reduction in the variable operating cost is achieved. For heat grids with a hot water storage tank, the reduction of the variable operating cost is 44% greater (-2.6 vs. -1.8 MSEK/yr). For heat grids without a hot water storage tank, the decrease is 13% greater (-3.6 vs. -3.2 MSEK/yr), which is probably because thermal storage in buildings centrally located in the network has greater value because there is no hot water storage tank there.

Table 31. Variable operating cost for reference case (no flexibility) and for cases with Thermal storage in buildings 20% (absolute and relative to reference case). Archetype heat grid: GHP and GHP S and the same heat grid but with 10% of the heat demand in a satellite

	With storage tank (S)	Without storage tank
Extra grid heat pump (GHP) **No satellite**	**No flexibility** 104.6 MSEK/yr **Thermal storage in buildings 20%** 102.7 MSEK/yr -1.9 MSEK/yr -1.8%	**No flexibility** 109.1 MSEK/yr **Thermal storage in buildings 20%** 105.6 MSEK/yr -3.5 MSEK/yr -3.2%
Extra grid heat pump (GHP) **10% of heat demand in satellite**	**No flexibility** 106.7 MSEK/yr **Thermal storage in buildings 20%** **All flexibility centrally** 104.9 MSEK/yr -1.8 MSEK/yr -1.7% **Thermal storage in buildings 20%** **Half of flexibility in satellite** 104.1 MSEK/yr -2.6 MSEK/yr -2.4%	**No flexibility** 110.8 MSEK/yr **Thermal storage in buildings 20%** **All flexibility centrally** 107.6 MSEK/yr -3.2 MSEK/yr -2.9% **Thermal storage in buildings 20%** **Half of flexibility in satellite** 107.2 MSEK/yr -3.6 MSEK/yr -3.9%

5 Reducing capacity demands

Flexible heat demand creates the opportunity to reduce capacity requirements in heat generation and distribution grids. There is a fundamental difference between the three types of flexibility studied in this project:

- Thermal storage in buildings: Thanks to flexible control of heating systems in the buildings, the maximum heat load of the network can be reduced.
- Heat source shifting: District heat – Heat pump: The normal case (no flexible control of heat pumps) at maximum heat load is that all building heat pumps (BHPs) supply their maximum power. It is thus the existence of the BHPs—and not their flexible control—that reduces the maximum heat load in the DH grid.
- Borehole storage connected to buildings: The normal case (no flexible control of the storage) at the design load is that the borehole storage will likely deliver its design power, since the buildings' heat load profile has a very strong correlation with the heat grid's health load. It is the existence of the borehole storage—and not its flexible control—that reduces the maximum heat load in the DH grid.

For this reason, only thermal storage in buildings will be studied in detail in this chapter. The reduction of the maximum power of the other types of flexibility is as follows:

Heat source shifting: District heat – Heat pump: 1.8 MW

Borehole storage connected to buildings: 2.3 MW

This design heat demand reduction should be included when dimensioning heat generation and distribution capacity if the BHPs and Borhole Storage are in operation during the design conditions (which should be the normal case).

5.1 REDUCING DESIGN POWER

The demand profile is independent of fuel mix, but it is very important whether or not there is a hot water storage tank in the system. Therefore, only two types of heat grids, with and without hot water storage tank, are studied. The results are then valid for all six archetype heat grids.

The reference case for the coldest day in 20 years (which also includes the coldest hour in 20 years) is shown in Figure 21 for archetype heat grids without hot water storage tanks. The day before and day after have been added to the figure to give a clearer picture. The hour with the highest heat demand has an upper confidence interval (90%) of 208 MW, which is the capacity required to most likely satisfy full heat demand without utilizing any flexibility. It is to this value that reductions in design heat load will be compared.

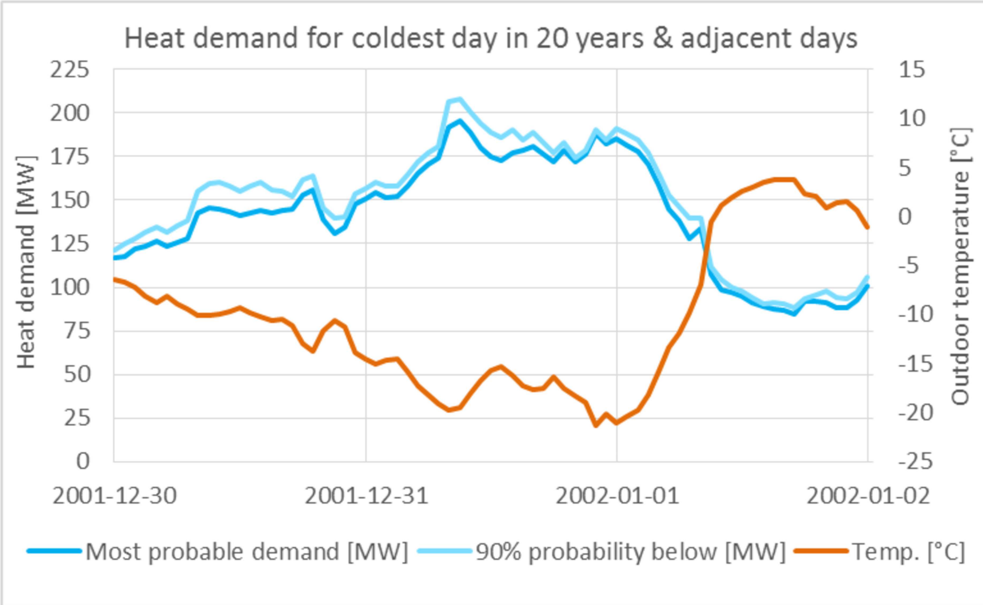


Figure 21. Heat demand profile for coldest day in 20 years and adjacent days. The design heat demand for the upper confidence interval and hence the required capacity is 208 MW

The significantly longer period of cold weather shown in Figure 22 ends with the period with the lowest five-day average temperature over the last 20 years. The figure also shows the four days (containing one very cold day) that occurred just before the five-day period. Thus, a total period of nine days is analyzed. The design heat demand for confidence intervals (90%) during this period is 207 MW, only 1 MW less than during the coldest day in Figure 21. This maximum power occurs during the second day of the period.

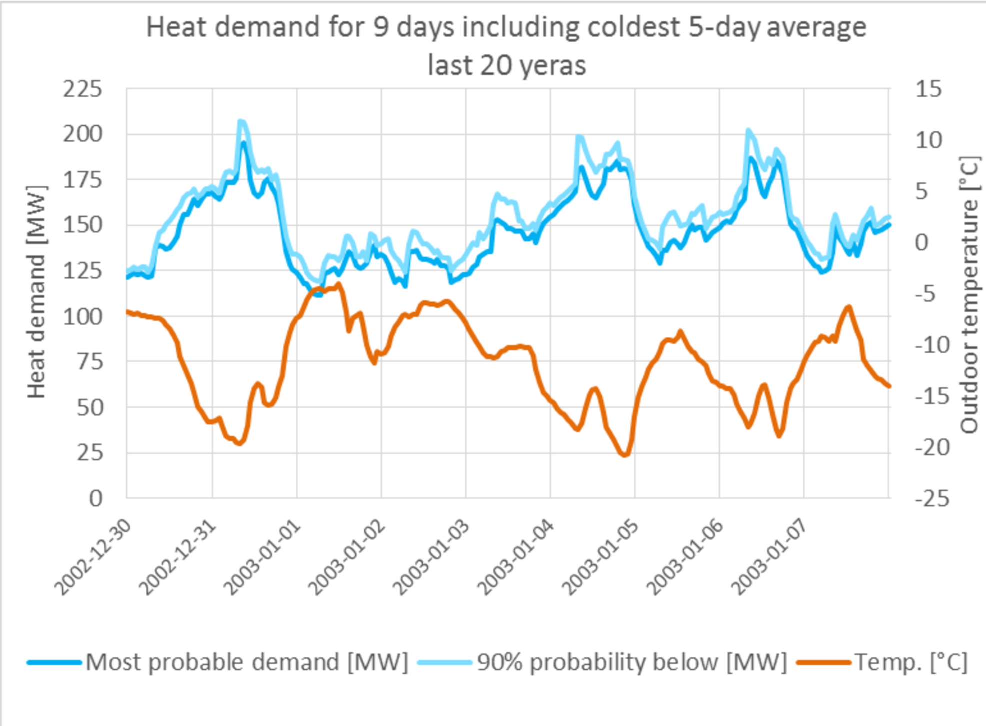


Figure 22. Heat demand profile for period containing the lowest five-day average temperature for the last 20 years. The design heat demand for the upper confidence interval, and hence the required capacity, is 207 MW

By implementing thermal storage in buildings, the required (generation and distribution) capacity to meet all heat demands can be reduced. This is exemplified for case: Thermal storage in buildings 44% (the 287 best suited properties are utilized), shown in Figure 23 and Figure 24. The limit on additional indoor temperature variation allowed in this analysis is the same as that in normal daily optimization (presented in Chapter 4 The value of flexible heat demand) of thermal storage in buildings (±0.5°C). The power limitation of the control is calculated against the upper confidence interval (at each individual hour there must be enough capacity to handle a heat demand corresponding to the upper confidence interval), but energy in thermal storage in buildings (and a hot water storage tank) has been calculated against the most likely heat demand. The green line should therefore be compared with the upper confidence interval as it also includes the uncertainty in the model. In this case, the maximum heat load for both time periods studied is reduced to 188 MW. The area under Most likely demand (dark blue line) and Heat demand with flex (green line) differs because there is a net discharge of the thermal storage in the buildings during the period. The charge level and thus the indoor temperature in the buildings are higher at the beginning of the periods than at the end of the periods. The variation is within the allowed range (±0.5°C), and recovery takes place in the days after the studied period.

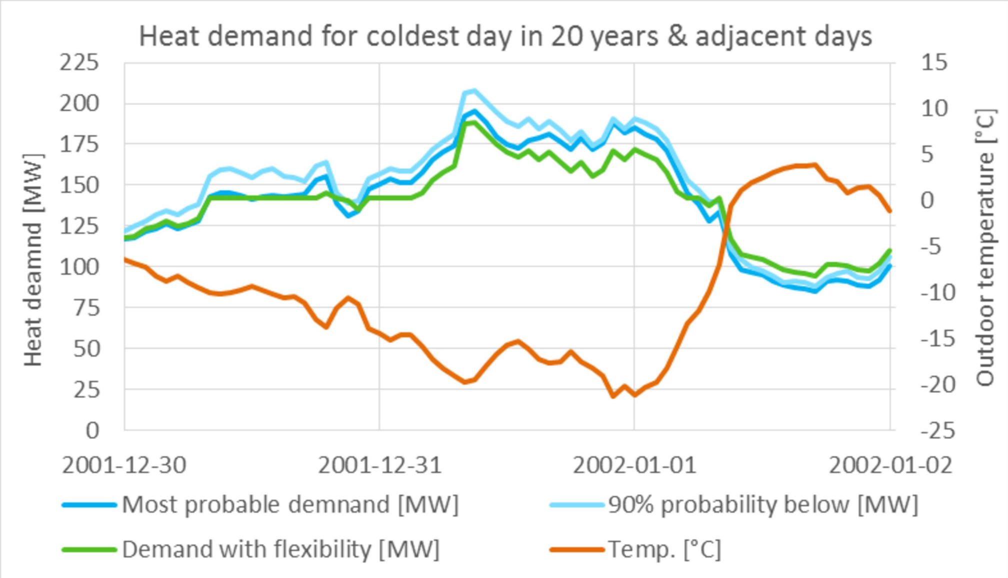


Figure 23. Heat demand profile for coldest day in 20 years and adjacent days for case: Thermal storage in buildings 44%. Extra variation in indoor temperature ±0.5°C. Required capacity: 188 MW

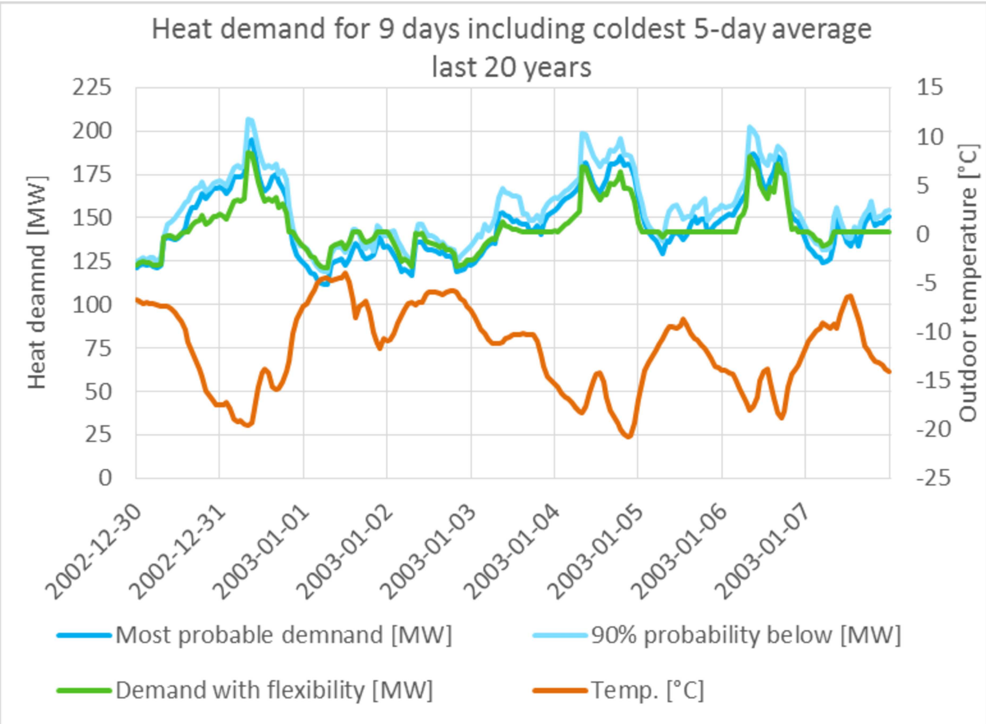


Figure 24. Heat demand profile for period containing the lowest five-day average temperature for the last 20 years for case: Thermal storage in buildings 44%. Extra variation in indoor temperature ±0.5°C. Required capacity: 188 MW

In the archetype heat grids that have a hot water storage tank, much of the potential for reducing capacity requirements is already taken by the hot water storage tank. This is shown in Figure 25. In all archetype heat grids with a hot water storage tank, the tank has a storage capacity of 500 MWh and a maximum power of 50 MW. Unlike in the optimization during normal circumstances (all periods with heat demand not close to design conditions), the entire hot water storage tank capacity is used to cut the peak heat demand. However, there remain opportunities to further reduce capacity needs through thermal storage in buildings, as shown in Figure 26. The reason why only the longer cold period (which includes the coldest five days) is shown is that this period has the highest capacity need when flexibility is considered. Although the hot water storage tank has already reduced the capacity requirement to 157 MW, it can be further reduced to 144 MW by thermal storage in buildings.

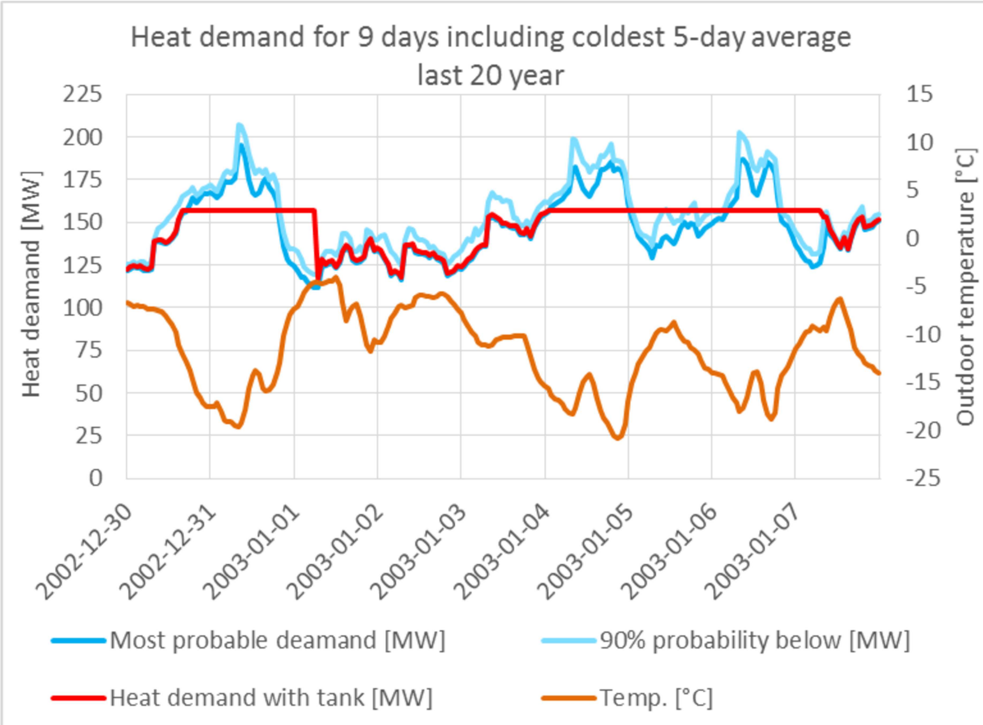


Figure 25. Heat demand profile for period containing the lowest five-day average temperature for the last 20 years, for reference case (without flexible demand). Heat grid with hot water storage tank. Required capacity: 157 MW

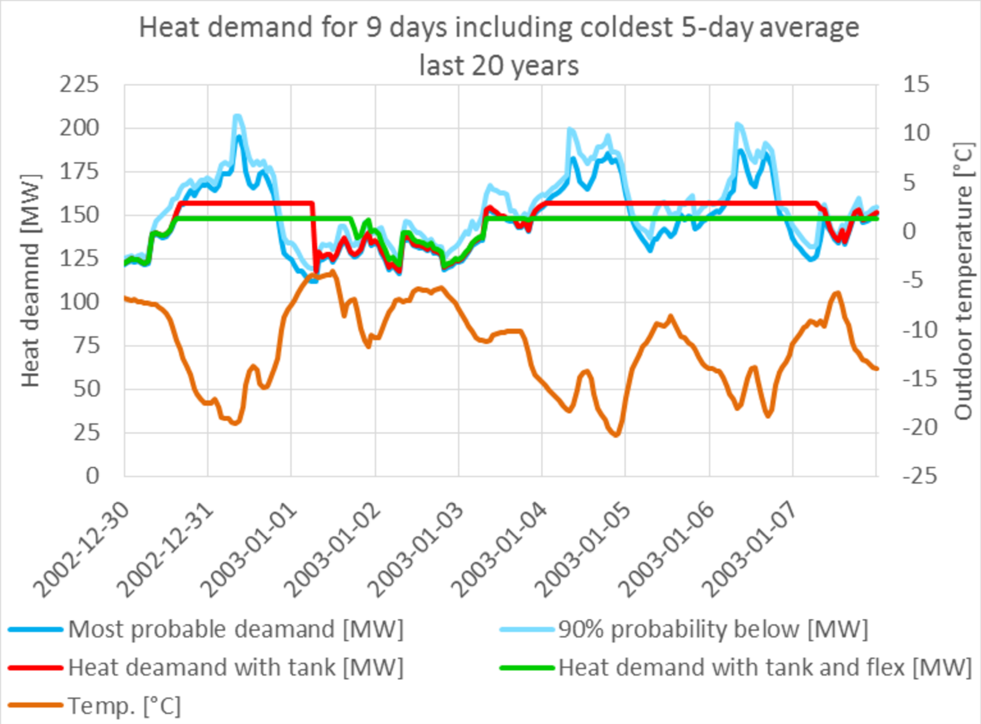


Figure 26. Heat demand profile for period containing the lowest five-day average temperature for the last 20 years, for case: Thermal storage in buildings 44%. Extra variation in indoor temperature ±0.5°C. Heat grid with hot water storage tank. Required capacity: 144 MW

The above results are based on a case where the extra variation in indoor temperature is limited to ±0.5°C. Variations within this range should normally not be noticed by the occupants in the buildings and are classified as good indoor climate according to the current ISO standards (ISO7730, 2005). If the range of allowed indoor temperature variation is allowed to increase during days when the heat demand is close to design condition, then there is an opportunity to reduce capacity requirements even more. Figure 27 shows an example of where the heat generation can be kept at a constant power for a whole week with high varying heat demand. This is achieved thanks to a combination of hot water storage tank and thermal storage in buildings with an indoor temperature that is allowed to vary within a range of -2.5 to +0.5°C from what it is with no active thermal storage in the buildings. It should be noted, however, that the model used for thermal storage in buildings is not validated against practical tests with such strong control signals so the uncertainty in the results is greater (than for the study with variation within ±0.5°C).

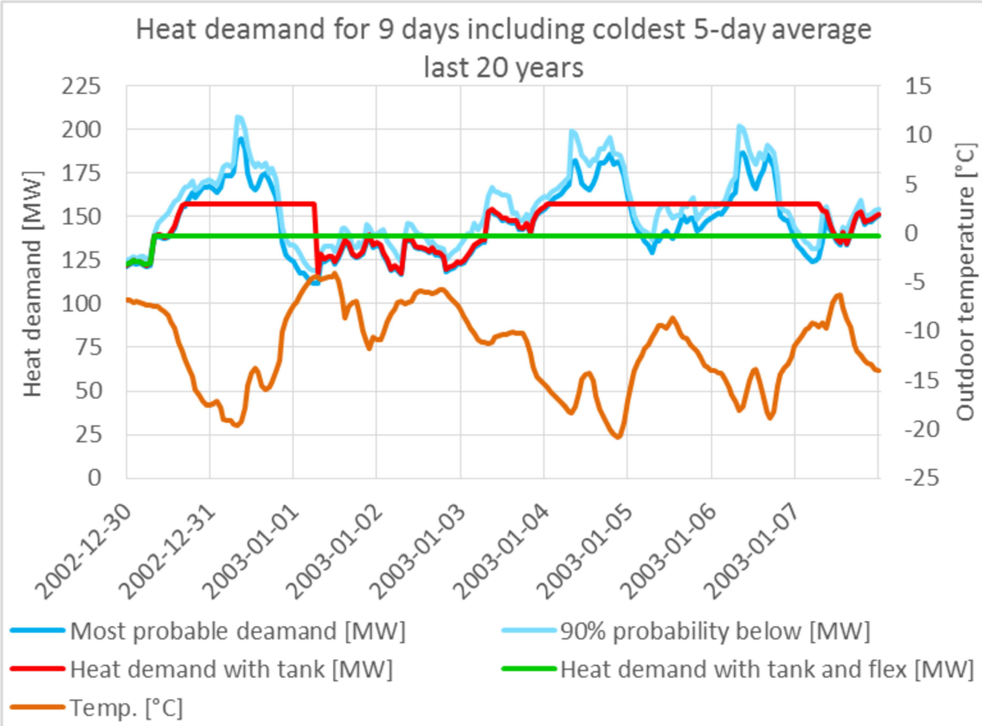


Figure 27. Heat demand profile for period containing the lowest five-day average temperature for the last 20 years for case: Thermal storage in buildings 44%. Extra variation in indoor temperature -2.5 to +0.5°C. Heat grid with hot water storage tank. Required capacity: 139 MW

The ability to reduce capacity requirements through thermal storage in buildings for archetype heat grids with and without a hot water storage tank has been compiled in Table **32**. However, it should be kept in mind that this is a theoretical analysis requiring a well-thought-out strategy for how the buildings' thermal inertia should be utilized and assuming that there is an accurate forecast model for the heat demand in the grid in order to efficiently reduce the highest heat demand and therefore the required capacity.

Table 32. Capacity (generation and distribution) needed to meet all heat demands. Reductions are relative to the reference case (without flexible demand)

	With storage tank (S)	Without storage tank
Reference case (without flexibility)	158 MW	208 MW
Thermal storage in buildings 20% **Normal control: ±0.5°C**	150 MW -5.1%	199 MW -4.3%
Thermal storage in buildings 20% **Stronger control: -2.5/+0.5°C**	143 MW -9.5%	190 MW -8.7%
Thermal storage in buildings 44% **Normal control: ±0.5°C**	144 MW -8.9%	188 MW -9.6%
Thermal storage in buildings 44% **Stronger control: -2.5/+0.5°C**	139 MW -12.0%	169 MW -18.8%

5.2 EXAMPLE OF ECONOMIC VALUE

The building and maintaining of infrastructure for heat generation capacity and distribution in DH grids is associated with considerable costs. These costs can be divided into four categories:

- (Re)investment cost for heat generation facilities
- Fixed maintenance and overhead cost for heat generation facilities
- (Re)investment cost for distribution grid
- Fixed maintenance and overhead cost for distribution grid

These costs refer only to those that are independent of how much the infrastructure is utilized (variable maintenance and overhead cost have already been included as part of the variable operational cost in the simulations). By reducing capacity demand, the related cost can be reduced. The value of 1 MW of reduced capacity demand varies between different DH grids and also depends on where on the heat grid the demand for capacity is reduced. Mapping these costs for different types of networks is outside the scope of this project, but a calculation example is presented.

Design heat demand in the archetype heat grids involves two oil HOBs with a capacity of 10 MW and 20 MW, respectively. Only the investment cost for these facilities is about 1.2 MSEK/MW (Hagberg, et al., 2017). The investment avoided for the four cases studied for the archetype heat grids with and without a hot water storage tank is presented in Table **33**. Avoidance of investment per property utilized for thermal storage in buildings is in the range of 59–332 tSEK. These values are based on the assumption that the possibility for controlling the heat load in the buildings can be counted as capacity on the same terms as, for example, a HOB. In any case, the table only shows one of four significant capacity-related costs. Investing in the possibility of limiting the maximum heat load under design conditions in a careful selection of properties should be a very cost-effective alternative to investing in and maintaining heat generation and distribution capacity.

Table 33. Avoided alternative investment in heat generation capacity due to thermal storage in buildings

	With storage tank (S)	Without storage tank
Thermal storage in buildings 20% (65 properties) Normal control: ±0.5°C	Total: 10 MSEK Per property: 148 tSEK	Total: 11 MSEK Per property: 166 tSEK
Thermal storage in buildings 20% (65 properties) Stronger control: -2.5/+0.5°C	Total: 18 MSEK Per property: 277 tSEK	Total: 22 MSEK Per property: 332 tSEK
Thermal storage in buildings 44% (287 properties) Normal control: ±0.5°C	Total: 17 MSEK Per property: 59 tSEK	Total: 24 MSEK Per property: 84 tSEK
Thermal storage in buildings 44% (287 properties) Stronger control: -2.5/+0.5°C	Total: 23 MSEK Per property: 79 tSEK	Total: 47 MSEK Per property: 163 tSEK

6 Discussion

The purpose of the discussion chapter is primarily to reflect on the assumptions that have been made and how the simulation study results relate to expectations of real application of flexible heat demand in DH grids.

What impact does a perfect forecast have on the results? All optimization in this project is based on a perfect forecast and a relatively long optimization horizon of 1–2 months. This applies to all parameters, for example, weather, heat demand, heat losses, electricity prices, electricity certificate prices, fuel prices, performance/availability of boilers, and how buildings will react to control signals. The biggest consequence of this is that there is no need for a safety margin in the optimization. For example, if 107.2 MWh of heat needs to be stored in a hot water storage tank at 16:00 in order to avoid starting an oil HOB, there will be exactly 107.2 MWh of heat stored at 16:00. In a real scenario there are uncertainties, and one would likely want there to be at least 150 MWh of stored heat at 16:00 to be quite sure of not having to start the oil HOB. This "over-optimization" means that flexibility becomes more valuable than it really is. However, this also applies to thermal storage in the distribution grid and the hot water storage tank already in the reference case. Since all simulations with flexible demand are compared with the reference case, the effect on the difference between the scenarios is limited, but one should keep in mind that this is a study of maximum potential.

How representative is the simulation period 2015–2017? The presented results are average values for the three simulation years of 2015, 2016, and 2017. A period of three years has been chosen because the heat demand profile can be vary greatly over different years, and these three years include a "warm year" (2015), a "cold year" (2016), and a "normal year" (2017). This is of particular importance for the utilization of HOBs, which can be much higher during years with very cold winter months. January 2016 was such a cold month, and that month accounts for more than half of all heat generation with oil HOBs over all three years for most of the archetype heat grids and simulation cases. Another important factor is the electricity price that is relatively low in all three years; in 2018, the subsequent year, however, it was significantly higher. This should have the greatest impact on the flexibility type Heat source shifting: District heat – Heat pump. At higher electricity prices, the building heat pumps (BHPs) should be shut down more often and the savings of turning them off should be greater (especially when CHP is on the margin in the DH grid).

Are there other forms of value of flexible demand that are not included in the study? Below are listed a few potential additional types of value identified but not studied or quantified:

- **Extra security against, for example, incorrect forecasts:** In cases where a heat demand forecast turns out to be incorrect or a boiler unexpectedly becomes inaccessible, flexible demand can be a way to handle the deviation. This requires that the flexibility be controlled directly by the operational personnel.

- **Electricity trading on intraday and/or regulating market:** With increased flexibility there is an increased opportunity to act on the electricity market with shorter notice. This applies to electricity generated in CHP as well as electricity used in heat pumps in DH grids (and in buildings if it is legally/practically feasible).
- **Increased competitiveness:** Customers can be offered lower prices or other benefits if they offer their flexibility to the DH operator. Alternatively, customers can be offered more dynamic price models that reward those customers who act on price signals from the DH operator. In any case, it is positive for both image and customer relations if customers are invited to be part of the smart energy system
- **Reduce capacity-related fixed cost:** The ability to reduce capacity requirements through flexible demand has only been quantified for investment cost in heat generation capacity. In addition, investment cost in distribution grids and maintenance cost for both generation and distribution can be avoided. Alternatively, a reduced capacity requirement for an existing customer base can be seen as an opportunity to connect more customers to the same infrastructure without having to expand it.

How is the value of flexibility shared between actors? The optimization in this study maximizes the overall economic value of flexibility but does not take into account who is benefitting from it. Those who are mainly affected are property owners and the DH company, but electricity traders are also affected because the electricity for heat pumps in real estate is optimized against Nordpool's hourly rates without surcharges (in addition to energy tax, electricity certificates, grid fee). Suppliers of excess heat can also be affected. Business models are needed to distribute the value that arises between all parties involved.

If thermal storage in buildings is implemented according to the optimization carried out in this study, and no changes are made in the current business and price models, the value will still be distributed between DH companies and property owners. In the reasoning below Table **12**, it is shown that 71–94% of the reduction in variable operating cost is due to a reduction in the cost per MWh generated heat, and 6–29% of the reduction is due to the reduction in the amount of MWh heat generated. This is because the optimization usually executes a control in which indoor temperatures lie in the lower part of the allowed range (down to 0.5°C lower than a case with no active thermal storage), which reduces heat losses. Reduction of cost per MWh generated will benefit only the DH company, but the reduction in the number of MWh generated (and any margin in the sale of this heat) will be transferred financially to the property owner through reduced sales. It should also be added that more advanced control systems in buildings (for example, with feedback from indoor temperature, model for thermal inertia, and/or forecast for several weather parameters) should be installed in properties that are to be used as thermal storage to guarantee the indoor climate. This type of control system in itself often has an energy-saving effect relative to traditional systems (an outdoor temperature sensor that controls the set point for supply temperature in radiator systems and thermostats on radiators that regulate flow) which is in the order of 10% (Olsson, 2014). This energy saving is not included in this study and only arises if the implementation of thermal storage in buildings entails an upgrade to more advanced control systems in the properties utilized.

In addition to value linked to energy saving and reduced heat generation cost, capacity-related cost can also be brought down by reducing the design heat demand in the heat grid. If the current pricing model includes a subscribed power (or flow), then value is transferred to the customer if the thermal storage in building control enables the customer to reduce subscribed power. For power tariffs based on measured heating power or a heating power signature, little or none of this value is transferred to the customer because heat demand close to design value is very rare. On the other hand, daily optimization can lower the customers' power tariff because it tends to reduce heat load at the occasions on which the power tariff calculation are based.

The above remarks and results from the simulation should be taken into consideration (together with a possible deeper study of the value of a specific DH grid that will start utilizing thermal storage in buildings) to develop business models that distribute the value of thermal storage in buildings between DH companies and building owners. How investment cost are distributed between DH companies and building owners should also be taken into account. Listed below are examples of concepts that may be worth investigating further (in no particular order):

- More dynamic prices for district heat, which gives building owners an incentive to move heat use to times with low generation cost. This can be anything from spot prices based on current generation cost to simpler and more predictable price models such as different prices for different times of day or prices that depend on outdoor temperature (time of day and outside temperature has strong correlation with marginal cost for heat generation).
- Request or auction system where a more traditional price model is the basis of the heat price, but the DH company can at any time publish offers for building owners to temporarily increase or decrease their heat load. Some type of business logic or open auction system decides which building should adjust their heat demand and how much they are compensated for doing so. Such a system can seek inspiration from how intra-day trading works, for example, on Nordpool.
- Thermal storage in buildings is standard in all contracts with customers, and customers are indirectly compensated for their flexibility through lower prices in general. This solution is probably more suitable in networks where thermal storage in buildings is primarily a method for reducing capacity demand and is only used close to design heat demand or in situations such as problems with boilers.
- A fixed discount or reduction of the power tariff is offered to customers who allow their flexibility to be freely used by the DH company within given limitations (e.g., maximum heating power that is allowed for the control system to adjust and/or maximum variation in indoor temperature).

- Customers are offered discounted (or free) services for their buildings (utilized for thermal storage) being equipped with upgraded control systems and/or indoor temperature sensors. The customer can then benefit from energy saving and/or the opportunity to better analyze the climate and energy performance in their buildings.
- Trust model where the value created by thermal storage in buildings is calculated retrospectively and shared among the actors who have contributed (proportionate to their contribution). This model could work for case with one or more major housing companies (e.g., municipality owned housing companies, which often have the same owner as the local DH company).

If Heat source shifting: District heat – Heat pump is implemented according to the optimization carried out in this study and no changes are made in the current business and price models, there is a great risk that the value will be distributed unevenly and that the building owner will lose financially through this type of control. This is because the building owner usually has energy prices for electricity and district heat that are constant for at least a one-month horizon. Which heat source has the lowest cost for the property owner is constant (and it is usually heat from the heat pump, with the exception of the summer months in some DH grids), so there is no value in flexible control for the building owner. The economic value benefits the DH company through increased sales, which are linked to increased heat generation during hours with low marginal cost. The building owner's electricity provider can earn or lose on this deal depending on how the average purchase price of the electricity changes in relation to their margins. In any case, a business model that distributes the value is necessary for this type of flexibility to be attractive for all parties. There may also be extra value to be obtained if the business model enables electricity used in BHPs to be traded on intraday and/or regulating markets. Some examples of business models that can be valuable to investigate further are as follows:

- Spot prices on all district heat or just the heat that can otherwise be replaced by BHPs. The building owner should preferably have spot prices for electricity (but it is also possible without) and install a control system that selects the heat source with the lowest operational cost every hour.
- An agreement that allow DH companies to switch off BHPs, but if it is done, the corresponding amount of district heat must be sold at a price that is lower than what the heat from the heat pump would otherwise have cost the property owner.
- DH companies are responsible for controlling heat pumps in buildings, and the building owner pays an energy price for the heat that is used in the building regardless of whether the heat comes from DH or heat pump.

The reduced variable operating cost in Flexible operation of borehole bearings (relative to the fact that the borehole bearing is not controlled flexibly) primarily accrues to the DH company in the current commonly used price models. This is because heat prices are static on a monthly basis and the same amount of heat is charged/discharged from the borehole every month. Because this type of flexibility probably includes much larger (and fewer) installations than the other types of flexibility, there is room for more customized solutions for each implementation. There are several types of layouts that can be valuable to investigate further for such an implementation.

- DH companies invest in the borehole and offer properties in the vicinity high-temperature heat (directly from DH) for domestic hot water and medium-temperature heat (from boreholes) for heating. The DH company then has a free hand to utilize the warehouse in its optimization.
- Property owners who invest in boreholes are offered incentives for the borehole bearing to be loaded when margin cost is at its lowest in the DH grid and/or to prioritize discharge when marginal cost is at its highest. These incentives can be anything from spot prices to a fixed price of a certain amount of heat per week/month during the summer (which DH companies choose when to deliver).
- A confidence model in which value created by borehole bearings and its flexible control is calculated every year and distributed between DH companies and real estate companies (according to any proportion that is also based on each partner's investment).

Regardless of which business model is used for the three types of flexibility, it is probably of great value to follow up and calculate environmental value that arises through the use of demand flexibility. All interested parties should see a value in this information that can be used for everything from communication with end users to the basis for decisions by decision makers.

The reduced variable operating cost from flexible control of Borehole storage connected to buildings (relative to the case where the borehole storage is not controlled flexibly) primarily accrues to the DH company in the current, commonly used price models. This is because district heat prices are static on a monthly basis and the same amount of heat is charged/discharged from the borehole storage each month. Because this type of flexibility probably includes larger (and fewer) installations than the other types of flexibility, there is room for more customized solutions for each implementation. Several types of business models can be used to further investigate such an implementation:

- DH companies invest in the borehole storage and offer buildings in the vicinity high-temperature heat (directly from the DH grid) for domestic hot water and medium-temperature heat (from borehole storage) for space heating. The DH company is free to control the borehole storage and use it to better plan and optimize heat generation in the system.
- Building owners who invest in boreholes are offered incentives for the borehole storage to be charged when marginal cost of heat generation is at its lowest in the DH grid and/or to prioritize discharge of the storage when marginal cost is at its highest. This can be anything from spot prices to a fixed price for a certain amount of heat per week/month during the summer (which DH companies choose when to deliver).

- Trust model, where the value created by borehole storage and its flexible control is calculated every year and distributed between the DH company and building owners (proportionate to each partner's investment).

Regardless of which business model is used for the three types of flexibility, it is probably of great value to follow up and calculate environmental value that arises from the use of flexible heat demand. All interested parties should see value in this information that can be used in everything from communication with end users to input for policymakers and companies.

7 Conclusion and suggestions for further studies

A review of energy performance certificates for four cities has resulted in an assessment of how much flexible demand it is possible to utilize in DH grids. If the results are scaled to an archetype heat grid with an annual heat generation of 500 GWh, it is possible to access flexible heat demand with a maximum power of 9 MW and a thermal storage capacity of over 340 MWh, of which 45 MWh is so-called fast flexibility that can be utilized combined with the maximum power. This implementation of thermal storage in buildings reduces the variable operating cost by 1.8–4.4% in the archetype heat grids with a hot water storage tank. In the heat grids without a hot water storage tank, the reduction in operating cost is almost twice as large (3.2–8.1%). If the savings are distributed among the properties utilized, the value per property is 53–62 tSEK/yr. At the same time, a reduction in CO2e of 1.1–1.7 kton/yr was achieved and a balancing effect on the electricity grid could be noted but not quantified. If the 287 best suited properties are utilized (corresponding to 44% of the heat load), the available flexibility can more than double. This results in a doubling of the reduction in variable operating cost and a reduction in CO2e. On the other hand, the value per utilized property is considerably lower, since many smaller properties are utilized (21–25 tSEK/yr for archetype heat grids without a hot water storage tank). The value of thermal storage in buildings has also been shown to be greater if the buildings that are utilized are located in a part of the network where the transmission capacity is limited. In summary, these numbers show that the technology of thermal storage in buildings can create great value in many types of DH grids.

Based on the four cities studied, there should be about 81 properties with both exhaust air heat pump and DH in an archetype heat grid with an annual heat generation of 500 GWh. These heat pumps should have a combined maximum heat output of 1.8 MW. Exhaust air heat pump is by far the most common heat pump installation to combine with DH. If these heat pumps are controlled flexibly, the combined operating cost of the DH grid and the heat pumps in buildings (BHPs) can be reduced by 0.22–1.12 MSEK/yr. The reduction is greatest for heat grids with a lot of excess heat and smallest for heat grids with large heat pumps such as heat source heat pumps. The presence of a hot water storage tank in heat grids that utilize BHPs for flexible control has very little impact on the results. If the savings are distributed per utilized BHP, they are 2.7–13.6 tSEK/yr and heat pump which can also be expressed as 120–610 tSEK per year and MW controllable heat output from BHPs. A total reduction in CO2e (combined from DH + BHPs) of 0.4–2.3 kton/yr is also achieved. Whether this type of control has a balancing effect on the electricity grid is not clear since the BHPs consume relatively more electricity at high electricity prices when they are flexibly controlled. This is because the marginal cost in the DH grid tends to vary more and be low at low electricity prices. However, the balancing effect on the electricity grid from the CHP in DH networks increases if the heat pumps in the properties are controlled flexibly.

For the case with Borehole storage connected to buildings that is controlled flexibly, a reduction in variable operational cost of 600–1,360 tSEK/yr (relative to a reference case with no borehole storage) is achieved. This reduction is 36–133% greater than if the borehole storage is not controlled flexibly. Borehole storage is most profitable in archetype heat grids with excess heat, since they have the largest difference between marginal cost in summer and winter. However, the environmental benefit is greatest in heat grids with CHP on the margin during the summer (instead of excess heat), because the heat from CHP is assumed to have negative CO2e emissions from a system perspective.

If all three types of flexible demand are combined, then the sum of the reduction in operational cost that they provide individually is about the same as that if they are combined in one simulation. This indicates that they fill different functions in the optimization of heat generation and that there is no diminished return by combining them. This applies not only to economic benefits but also to reduction of CO2e.

Flexible heat demand can also be used to reduce the need for heat generation and distribution capacity in DH grids. For the case with the 65 best suited properties (corresponding to 20% of the heat demand in the archetype heat grids), the maximum 20-year design heat demand can be reduced by 9 MW in heat grids without a hot water storage tank and by 8 MW in heat grids with a hot water storage tank. If a stronger control signal is allowed where the indoor temperature drops by up to 2.5°C under design conditions, the reduction in design heat demand is almost doubled. Only alternative investment in an oil HOB to cover this capacity requirement amounts to 148–332 kSEK per property utilized for thermal storage in buildings in the cases presented above. In addition to this value, investment cost in distribution and maintenance cost for production and distribution can be avoided.

Thus, great value seems to be gained from investing in flexible heat demand for many DH companies. Relatively few major investments have been made, though, and the content of this study will hopefully lead to more DH companies making profitable investments in flexible heat demand. A number of areas require further study, however.

Suggestions for further study

Business models that distribute savings, investment, and risk between the involved actors are a prerequisite for successful large scale implementation of flexible heat demand. Because demand flexibility creates savings and other benefits that can be difficult to measure, this is a challenge. A number of thoughts on this topic have been highlighted in Chapter 6 Discussion that can be used as input for creating and analyzing business models, and it is likely that no one model will fit all conditions. Different business models may be necessary for different customers and in different DH grids with different prerequisites.

Other types of flexibility and smart customer solutions can be studied with similar methods to those used in this project. There are real estate developers who show an interest in creating different "smart energy solutions" such as different types of thermal storage, solutions that combine district heat with other heat sources and/or local heating/cooling grids with different temperatures. Prosumers who require a heat pump to raise the temperature of the surplus heat are another example. DH companies need to have the ability to analyze what impact these solutions have if they are connected to DH and district cooling grids. This analysis is necessary in order to be able to develop a good business model and to themselves invest in this type of solution.

The balancing effect on the electricity grid can be studied in more detail and quantified. Which regulating benefits in the electricity grid can be provided by CHP and heat pumps (in heat grids and in buildings) if demand flexibility (hot water storage tanks and thermal storage in distribution grid) is best utilized in DH grids? What are the possibilities of also acting on the intraday electricity market and the regulating market?

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Appendix: Compilation of simulation data

Heat grid: Extra combined heat and power without hot water storage tank (CHP)

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20%	Thermal storage in buildings 44%	BHP flexible	Borehole not flexible	Borehole flexible	Combined flexibility
District heat							
Tot. variable operation cost [MSEK]	99.7	95.7	92.7	100.5	99.5	99.1	95.9
Total heat generation [GWh]	502.1	499.4	496.1	507.5	504.7	504.6	507.3
Heat from CHP biomass [GWh]	446.2	447.0	445.6	450.6	449.8	450.0	455.2
Heat from excess heat [GWh]	-	-	-	-	-	-	-
Heat from grid HP [GWh]	-	-	-	-	-	-	-
Heat from HOB biomass [GWh]	43.5	42.9	42.8	44.5	43.0	43.1	43.4
Heat from HOB gas [GWh]	11.1	8.5	7.1	11.1	10.6	10.3	7.9
Heat from HOB oil [GWh]	1.3	1.0	0.7	1.3	1.3	1.2	0.8
El from CHP biomass [GWh]	83.8	84.9	85.6	84.6	86.2	86.2	88.2
El to GHP [GWh]	-	-	-	-	-	-	-
Revenue sold el [MSEK]	34.4	35.3	36	34.8	35.3	35.4	36.7
Cost bought el [MSEK]	-	-	-	-	-	-	-
Avg. revenue sold el [SEK/MWh]	410.8	415.9	421.3	411.6	410.0	410.5	416.2
Avg. cost bought el [SEK/MWh]	-	-	-	-	-	-	-
CO2e total [kton]	-52.3	-54.0	-55.0	-52.9	-54.2	-54.4	-56.6
CO2e from fuel [kton]	12.9	12.1	11.5	13.0	12.8	12.7	12.0
CO2e from sold el [kton]	-65.2	-66.1	-66.6	-65.8	-67.0	-67.1	-68.6
CO2e from bought el [kton]	-	-	-	-	-	-	-
Number of starts of HOB	73	39	21	74	74	72	37
Building heat pumps (BHPs)							
Tot. variable operation cost [MSEK]	2.9	2.9	2.9	1.5	2.9	2.9	1.4
Total heat generation [GWh]	10.4	10.4	10.4	5.0	10.4	10.4	5.0
El till VP [GWh]	3.1	3.1	3.1	1.5	3.1	3.1	1.5
Cost bought el [MSEK]	2.9	2.9	2.9	1.5	2.9	2.9	1.4
Avg. cost bought el [SEK/MWh]	932.4	932.4	932.4	942.2	932.4	932.4	942
CO2e from bought el [kton]	2.6	2.6	2.6	1.3	2.6	2.6	1.3

Heat grid: Extra combined heat and power with hot water storage tank (CHP S)

Yearly average values for simulation period 2015 – 2017

	Reference case (no flexibility)	Thermal storage in buildings 20%	Thermal storage in buildings 44%	BHP flexible	Borehole not flexible	Borehole flexible	Combined flexibility
District heat							
Tot. variable operation cost [MSEK]	92.7	90.5	88.7	93.4	92.3	92.0	90.8
Total heat generation [GWh]	502.1	499.0	495.4	507.4	504.7	504.7	507.1
Heat from CHP biomass [GWh]	449.8	448.2	445.6	454.2	453.4	453.6	456.3
Heat from excess heat [GWh]	-	-	-	-	-	-	-
Heat from grid HP [GWh]	-	-	-	-	-	-	-
Heat from HOB biomass [GWh]	42.9	42.8	42.6	43.8	42.3	42.4	43.4
Heat from HOB gas [GWh]	8.6	7.3	6.7	8.6	8.2	7.9	6.9
Heat from HOB oil [GWh]	0.9	0.6	0.4	0.9	0.8	0.8	0.5
El from CHP biomass [GWh]	86.4	86.6	86.8	87.2	88.9	88.9	89.9
El to GHP [GWh]	-	-	-	-	-	-	-
Revenue sold el [MSEK]	36.9	37.1	37.4	37.2	37.8	37.9	38.6
Cost bought el [MSEK]	-	-	-	-	-	-	-
Avg. revenue sold el [SEK/MWh]	426.5	428.8	431.0	426.9	425.5	426.1	428.7
Avg. cost bought el [SEK/MWh]	-	-	-	-	-	-	-
CO2e total [kton]	-55.3	-55.9	-56.4	-55.8	-57.3	-57.3	-58.5
CO2e from fuel [kton]	11.9	11.5	11.2	12.0	11.9	11.8	11.5
CO2e from sold el [kton]	-67.2	-67.4	-67.6	-67.8	-69.2	-69.1	-70.0
CO2e from bought el [kton]	-	-	-	-	-	-	-
Number of starts of HOB	19	12	9	17	17	15	12
Building heat pumps (BHPs)							
Tot. variable operation cost [MSEK]	2.9	2.9	2.9	1.5	2.9	2.9	1.4
Total heat generation [GWh]	10.4	10.4	10.4	5.1	10.4	10.4	4.9
El till VP [GWh]	3.1	3.1	3.1	1.6	3.1	3.1	1.5
Cost bought el [MSEK]	2.9	2.9	2.9	1.5	2.9	2.9	1.4
Avg. cost bought el [SEK/MWh]	932.4	932.4	932.4	942.2	932.4	932.4	939.9
CO2e from bought el [kton]	2.6	2.6	2.6	1.3	2.6	2.6	1.3

Heat grid: Extra grid heat pump without hot water storage tank (GHP)

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20%	Thermal storage in buildings 44%	BHP flexible	Borehole not flexible	Borehole flexible	Combined flexibility
District heat							
Tot. variable operation cost [MSEK]	109.1	105.6	103.0	110.0	108.6	108.2	105.8
Total heat generation [GWh]	501.1	498.2	494.7	505.4	503.7	503.7	505.0
Heat from CHP biomass [GWh]	279.0	279.1	278.2	280.4	282.6	283.1	284.5
Heat from excess heat [GWh]	-	-	-	-	-	-	-
Heat from grid HP [GWh]	153.9	153.7	153.0	156.4	153.9	153.2	155.6
Heat from HOB biomass [GWh]	57.1	57.0	56.6	57.5	56.7	57.2	57.1
Heat from HOB gas [GWh]	9.9	7.6	6.3	9.9	9.5	9.2	7.0
Heat from HOB oil [GWh]	1.2	0.8	0.6	1.2	1.1	1.0	0.7
El from CHP biomass [GWh]	64.4	64.9	65.1	64.5	66.3	66.5	67.1
El to GHP [GWh]	49.7	49.7	49.5	50.6	49.7	49.5	50.3
Revenue sold el [MSEK]	26.3	26.7	27.1	26.3	27.0	27.1	27.6
Cost bought el [MSEK]	40.5	40.4	40.1	41.2	40.4	40.3	40.8
Avg. revenue sold el [SEK/MWh]	408.3	412.1	415.8	408.5	407.3	407.6	411.4
Avg. cost bought el [SEK/MWh]	814.3	812.2	810.6	814.1	813.7	813.7	811.4
CO2e total [kton]	1.6	0.5	-0.3	2.3	0.0	-0.4	-0.9
CO2e from fuel [kton]	9.6	8.9	8.4	9.7	9.6	9.5	8.8
CO2e from sold el [kton]	-50.1	-50.5	-50.6	-50.2	-51.6	-51.8	-52.2
CO2e from bought el [kton]	42.1	42.1	41.9	42.8	42.1	41.9	42.6
Number of starts of HOB	66	34	18	65	64	64	32
Building heat pumps (BHPs)							
Tot. variable operation cost [MSEK]	2.9	2.9	2.9	1.7	2.9	2.9	1.6
Total heat generation [GWh]	10.4	10.4	10.4	6.1	10.4	10.4	6.1
El till VP [GWh]	3.1	3.1	3.1	1.7	3.1	3.1	1.7
Cost bought el [MSEK]	2.9	2.9	2.9	1.7	2.9	2.9	1.6
Avg. cost bought el [SEK/MWh]	932.4	932.4	932.4	948.7	932.4	932.4	946.8
CO2e from bought el [kton]	2.6	2.6	2.6	1.5	2.6	2.6	1.5

Heat grid: Extra grid heat pump with hot water storage tank (GHP S)

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20%	Thermal storage in buildings 44%	BHP flexible	Borehole not flexible	Borehole flexible	Combined flexibility
District heat							
Tot. variable operation cost [MSEK]	104.6	102.7	101.0	105.6	104.3	104.0	103.1
Total heat generation [GWh]	501.4	498.0	493.9	505.5	503.9	503.9	504.7
Heat from CHP biomass [GWh]	281.2	280.3	278.6	282.5	284.8	285.2	285.4
Heat from excess heat [GWh]	-	-	-	-	-	-	-
Heat from grid HP [GWh]	153.8	153.6	152.7	156.1	153.4	153.4	155.3
Heat from HOB biomass [GWh]	57.9	56.9	56.4	58.5	57.7	57.5	57.4
Heat from HOB gas [GWh]	7.7	6.6	6.0	7.7	7.3	7.2	6.3
Heat from HOB oil [GWh]	0.8	0.5	0.3	0.8	0.7	0.6	0.3
El from CHP biomass [GWh]	65.9	65.7	65.8	66.0	67.8	68.1	68.2
El to GHP [GWh]	49.8	49.7	49.5	50.5	49.6	49.6	50.3
Revenue sold el [MSEK]	27.4	27.5	27.6	27.5	28.1	28.3	28.4
Cost bought el [MSEK]	40.2	40.2	39.9	40.8	40.0	40.0	40.6
Avg. revenue sold el [SEK/MWh]	416.7	418.1	419.4	416.9	415.3	415.3	416.8
Avg. cost bought el [SEK/MWh]	808.0	808.0	807.7	808.2	807.3	807.4	807.1
CO2e total [kton]	-0.3	-0.5	-1.2	0.3	-1.9	-2.2	-2.1
CO2e from fuel [kton]	8.9	8.5	8.2	8.9	8.8	8.8	8.4
CO2e from sold el [kton]	-51.2	-51.1	-51.2	-51.3	-52.7	-52.9	-53.1
CO2e from bought el [kton]	42.1	42.1	41.8	42.7	42.0	42.0	42.5
Number of starts of HOB	15	10	9	21	13	13	9
Building heat pumps (BHPs)							
Tot. variable operation cost [MSEK]	2.9	2.9	2.9	1.7	2.9	2.9	1.6
Total heat generation [GWh]	10.4	10.4	10.4	6.2	10.4	10.4	6.2
El till VP [GWh]	3.1	3.1	3.1	1.8	3.1	3.1	1.7
Cost bought el [MSEK]	2.9	2.9	2.9	1.7	2.9	2.9	1.6
Avg. cost bought el [SEK/MWh]	932.4	932.4	932.4	945.3	932.4	932.4	943.3
CO2e from bought el [kton]	2.6	2.6	2.6	1.5	2.6	2.6	1.5

Heat grid: Extra excess heat without hot water storage tank (EH)

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20%	Thermal storage in buildings 44%	BHP flexible	Borehole not flexible	Borehole flexible	Combined flexibility
District heat							
Tot. variable operation cost [MSEK]	47.0	43.2	40.6	47.7	46.1	45.6	42.8
Total heat generation [GWh]	501.7	498.7	495.2	508.9	504.3	504.3	508.6
Heat from CHP biomass [GWh]	160.4	160.2	159.3	164.6	159.5	159.0	163.1
Heat from excess heat [GWh]	296.6	297.3	297.0	298.6	301.0	301.9	304.6
Heat from grid HP [GWh]	-	-	-	-	-	-	-
Heat from HOB biomass [GWh]	33.6	32.8	32.1	34.5	33.2	33.2	33.2
Heat from HOB gas [GWh]	9.9	7.6	6.3	9.9	9.5	9.2	7.0
Heat from HOB oil [GWh]	1.2	0.8	0.6	1.2	1.1	1.0	0.7
El from CHP biomass [GWh]	27.3	28.1	29.1	28.2	27.6	27.5	29.5
El to GHP [GWh]	-	-	-	-	-	-	-
Revenue sold el [MSEK]	11.5	12.0	12.6	12.0	11.7	11.7	12.6
Cost bought el [MSEK]	-	-	-	-	-	-	-
Avg. revenue sold el [SEK/MWh]	423.1	427.5	432.5	423.9	422.9	423.4	429.3
Avg. cost bought el [SEK/MWh]	-	-	-	-	-	-	-
CO2e total [kton]	-14.5	-15.9	-17.1	-15.1	-14.9	-14.9	-17.1
CO2e from fuel [kton]	6.8	6.0	5.5	6.8	6.6	6.5	5.8
CO2e from sold el [kton]	-21.2	-21.9	-22.6	-22.0	-21.5	-21.4	-22.9
CO2e from bought el [kton]	-	-	-	-	-	-	-
Number of starts of HOB	80	41	22	79	78	77	37
Building heat pumps (BHPs)							
Tot. variable operation cost [MSEK]	2.9	2.9	2.9	1.0	2.9	2.9	1.0
Total heat generation [GWh]	10.4	10.4	10.4	3.2	10.4	10.4	3.1
El till VP [GWh]	3.1	3.1	3.1	1.1	3.1	3.1	1.0
Cost bought el [MSEK]	2.9	2.9	2.9	1.0	2.9	2.9	1.0
Avg. cost bought el [SEK/MWh]	932.4	932.4	932.4	947.2	932.4	932.4	944.8
CO2e from bought el [kton]	2.6	2.6	2.6	0.9	2.6	2.6	0.9

Heat grid: Extra excess heat with hot water storage tank (EH S)

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20%	Thermal storage in buildings 44%	BHP flexible	Borehole not flexible	Borehole flexible	Combined flexibility
District heat							
Tot. variable operation cost [MSEK]	42.4	40.6	39.0	43.2	41.6	41.2	40.2
Total heat generation [GWh]	500.9	497.7	494.1	508.1	503.5	503.5	507.6
Heat from CHP biomass [GWh]	160.4	159.9	158.8	164.5	159.3	159.2	162.7
Heat from excess heat [GWh]	299.6	298.6	297.4	301.7	304.2	304.5	305.7
Heat from grid HP [GWh]	-	-	-	-	-	-	-
Heat from HOB biomass [GWh]	32.5	32.0	31.7	33.5	32.0	32.0	32.6
Heat from HOB gas [GWh]	7.7	6.6	6.0	7.7	7.3	7.2	6.3
Heat from HOB oil [GWh]	0.8	0.5	0.3	0.8	0.7	0.6	0.3
El from CHP biomass [GWh]	28.8	29.3	30.0	29.7	29.2	29.2	30.7
El to GHP [GWh]	-	-	-	-	-	-	-
Revenue sold el [MSEK]	12.5	12.7	13.1	12.9	12.6	12.7	13.4
Cost bought el [MSEK]	-	-	-	-	-	-	-
Avg. revenue sold el [SEK/MWh]	432.7	434.7	436.3	433.6	432.9	433.7	436.7
Avg. cost bought el [SEK/MWh]	-	-	-	-	-	-	-
CO2e total [kton]	-16.5	-17.2	-18.0	-17.1	-16.9	-17.0	-18.4
CO2e from fuel [kton]	5.9	5.6	5.3	6.0	5.8	5.7	5.5
CO2e from sold el [kton]	-22.4	-22.8	-23.3	-23.1	-22.7	-22.8	-23.9
CO2e from bought el [kton]	-	-	-	-	-	-	-
Number of starts of HOB	19	18	11	17	17	17	12
Building heat pumps (BHPs)							
Tot. variable operation cost [MSEK]	2.9	2.9	2.9	1.0	2.9	2.9	1.0
Total heat generation [GWh]	10.4	10.4	10.4	3.2	10.4	10.4	3.2
El till VP [GWh]	3.1	3.1	3.1	1.1	3.1	3.1	1.1
Cost bought el [MSEK]	2.9	2.9	2.9	1.0	2.9	2.9	1.0
Avg. cost bought el [SEK/MWh]	932.4	932.4	932.4	943.0	932.4	932.4	940.6
CO2e from bought el [kton]	2.6	2.6	2.6	0.9	2.6	2.6	0.9

Heat grid: Extra grid heat pump without hot water storage tank (GHP) 10% av heat demand in satellite

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20% All flexibility centrally	Thermal storage in buildings 20% Half the flexibility in satellite
Heat generation centrally in grid (all heat sources except HOB oil 2)			
Tot. variable operation cost [MSEK]	106.1	103.1	104.0
Total heat generation [GWh]	497.8	495.0	496.0
Heat from CHP biomass [GWh]	278.3	278.3	278.5
Heat from excess heat [GWh]	-	-	-
Heat from grid HP [GWh]	154.1	153.9	153.8
Heat from HOB biomass [GWh]	56.8	56.5	56.7
Heat from HOB gas [GWh]	8.0	6.1	6.7
Heat from HOB oil [GWh]	0.6	0.3	0.4
El from CHP biomass [GWh]	64.9	65.6	65.4

El to GHP [GWh]	49.8	49.8	49.7
Revenue sold el [MSEK]	26.5	27.0	26.9
Cost bought el [MSEK]	40.6	40.4	40.4
Avg. revenue sold el [SEK/MWh]	408.3	412.6	411.7
Avg. cost bought el [SEK/MWh]	814.4	812.3	812.6
CO2e total [kton]	0.5	-0.6	-0.3
CO2e from fuel [kton]	8.9	8.3	8.5
CO2e from sold el [kton]	-50.5	-51.0	-50.9
CO2e from bought el [kton]	42.1	42.1	42.1
Number of starts of HOB	39	23	26
Heat generation in satellite (HOB oil 2)			
Tot. variable operation cost [MSEK]	4.7	4.5	3.2
Total heat generation [GWh]	3.5	3.4	2.4
CO2e from fuel [kton]	1.1	1.1	0.8

Heat grid: Extra grid heat pump with hot water storage tank (GHP S) 10% av heat demand in satellite

Yearly average values for simulation period 2015–2017

	Reference case (no flexibility)	Thermal storage in buildings 20% All flexibility centrally	Thermal storage in buildings 20% Half the flexibility in satellite
Heat generation centrally in grid (all heat sources except HOB oil 2)			
Tot. variable operation cost [MSEK]	102.1	100.4	101.1
Total heat generation [GWh]	498.3	494.9	496.0
Heat from CHP biomass [GWh]	280.3	279.3	279.6
Heat from excess heat [GWh]	-	-	-
Heat from grid HP [GWh]	153.9	153.6	153.8
Heat from HOB biomass [GWh]	57.5	56.6	56.7
Heat from HOB gas [GWh]	6.3	5.4	5.8
Heat from HOB oil [GWh]	0.2	0.1	0.1
El from CHP biomass [GWh]	66.6	66.6	66.3
El to GHP [GWh]	49.8	49.7	49.8
Revenue sold el [MSEK]	27.8	27.9	27.7
Cost bought el [MSEK]	40.2	40.2	40.2
Avg. revenue sold el [SEK/MWh]	417.5	418.9	418.6
Avg. cost bought el [SEK/MWh]	808.0	807.8	807.9
CO2e total [kton]	-1.4	-1.8	-1.3
CO2e from fuel [kton]	8.3	8.0	8.1
CO2e from sold el [kton]	-51.9	-51.8	-51.6
CO2e from bought el [kton]	42.1	42.1	42.1
Number of starts of HOB	17	9	9
Heat generation in satellite (HOB oil 2)			
Tot. variable operation cost [MSEK]	4.6	4.4	3.0
Total heat generation [GWh]	3.4	3.3	2.2
CO2e from fuel [kton]	1.1	1.1	0.7

THE VALUE OF FLEXIBLE HEAT DEMAND

It is possible to utilize considerable amounts of demand flexibility in district heating grids? With an extended system boundary that includes buildings, district heating grids, and connection to electricity grids, a co-optimization can be performed that creates great economic value for the economy as well as the environment.

This value has been mapped through a simulation study for six archetype district heating grids for the three flexibility types of thermal storage in buildings, heat source shifting: district heat – heat pump, and borehole storage connected to buildings.

The value created by demand flexibility can vary between the different types of heat grids, but there are generally good economic and environmental incentives for many types of district heating grids to invest in flexible demand.

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