THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

The future load curve of the Swedish building stock
– Interactions between the heating load and district heating

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Abstract

In line with global efforts directed against climate change, the building sector is required to undergo significant changes in terms of its energy management. This is the case for both the use of energy (reduced energy consumption) and the supply of energy (heat and electricity), and how these two interact. Thus, the overall aim of this work was to investigate potential flexibility of the energy demand in buildings, i.e., demand response (DR), and how it can affect the energy supply side. More specifically, we studied the potential of space heating DR in buildings to improve the operation and efficiency of district heating (DH) systems.

This work applies several techno-economic optimisation models, which include estimation of the space heating demand in buildings, as well as the optimal dispatch and utilisation of heat generation and thermal energy storage technologies in a DH system. By applying the developed models, we examine the potential for flexible space heating demand. In principle this is done through allowing for indoor temperature deviations from the set-point temperature. The present work applies the building stock of Gothenburg, Sweden, as a case study, and thus, studies the operation of the city's DH system. The interplay with the power sector is included in this work by using hourly electricity prices as input.

The results of this work indicate that a realised DR in buildings, allowing for indoor temperature deviations from a set-point temperature, significantly affects the cost optimal heating load of the city by smoothing the variations. We show that upward indoor temperature deviations of as little as +1°C can smoothen the short-term (daily) fluctuations of the system heating load by up to 20% over a year. The modelling results also indicate that the potential of DR in buildings to moderate short-term daily heat-load variations in a DH system is comparable to the use of a centralised thermal energy storage system, e.g., a hot-water tank. However, on longer time-scales (from few days to weeks), the performance of a centralised storage in smoothening variations is superior. The smoothening of the heating load results in more efficient heat generation: the heat supply and number of full-load hours of base-load units increase, while the peaking units decrease their output. The results indicate that the DR via 1°C overheating of buildings can lead to an 85% decrease in the number of starts and stops of peaking, fossil-fired heat generation units, leading to improved carbon footprint of the system. Finally, the availability of CHP plants and HPs in DH systems is proven to be mutually beneficial both to DH systems and the power sector.

Keywords: District heating, buildings, thermal energy storage, demand response, space heating, optimisation

List of publications

This thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. D. Romanchenko, E. Nyholm, M. Odenberger, F. Johnsson, Co-optimizing space heating demand of buildings and dispatch of heat generation plants in a district heating system, Proceedings of the 1st Latin America Conference on Sustainable Development of Energy, Water and Environment Systems, SDEWES 2018

II. D. Romanchenko, J. Kensby, M. Odenberger, F. Johnsson, Thermal energy storage in district heating: centralised storage vs. storage in thermal inertia of buildings, Energy Conversion and Management **162**, p. 36-38, 04.2018, DOI: 10.1016/j.enconman.2018.01.068

III. D. Romanchenko, M. Odenberger, L. Göransson, F. Johnsson, Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden, Applied Energy **204**, p. 16-30, 10.2017, DOI: 10.1016/j.apenergy.2017.06.092

Dmytro Romanchenko is the principal author of **Papers I-III**. Professor Filip Johnsson, who is the main academic supervisor and examiner, has contributed with discussions and editing to all three papers. Mikael Odenberger, who is the co-supervisor, has contributed with in-depth discussions and editing to all three papers. Emil Nyholm has contributed with method development, data processing, discussions and editing to **Paper I**. Johan Kensby has contributed with method development, discussions and editing to **Paper II**. Lisa Johansson has contributed with discussions and editing to **Paper III**.

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Table of Contents

Abbreviations and nomenclature

Abbreviations

BITES	Energy storage *via* Building Inertia Thermal Energy Storage
CHP	Combined heat-and-power
DH	District Heating
DR	Demand Response
EBUC	Energy Balance Unit Commitment
HOB	Heat-only Boiler
HP	Heat Pump
HWT	Energy Storage *via* Hot Water Tank
RDLV	Relative Daily Load Variations
RWLV	Relative Weekly Load Variations
TES	Thermal Energy Storage
UC	Unit Commitment
UCS	Unit Commitment with Storage

Nomenclature

Charge rate	The rate at which energy (heat) is accumulated in a TES system
Demand	The amount of energy required ("wanted") by a consumer in order to fulfil some need(s)
Demand response	Changes in the end-use patterns (e.g., energy use) of consumers from their normal consumption patterns in response to changes in some kind of incentive, e.g., time-dependent price signal
Discharge rate	The rate at which energy (heat) is retrieved from a TES system
Load	The amount of energy delivered to a consumer
Optimal dispatch	The short-term determination of the optimal operation of a number of generation units meeting the specified objective, e.g., fulfilling the system load at the lowest cost, subject to a number of constraints
Peak shaving	Demand response strategy, which implies a reduction in energy consumption during the peak-load hours
Storage capacity	Maximum amount of energy that can be stored in a TES system
Thermal inertia	Resistance to a change in temperature
Valley filling	Demand response strategy, which implies an increase in energy consumption during the low-load hours

1. Introduction

The rapid growth of the global population and the consequent continuous increases in energy consumption raise serious environmental pollution and climate change issues. In 2015, in Paris, almost 200 countries recognised the anthropogenic impact on climate change and agreed to direct their efforts to limiting the increase in global temperature this century to well below 2°C in relation to pre-industrial levels. To achieve this target, greenhouse gas emissions must be reduced in all economic sectors.

According to the International Energy Agency (IEA), around one-third of final energy consumption globally is linked to the buildings sector, making it responsible for about one-third of total global energy-related carbon dioxide (CO_2) emissions [1]. Furthermore, the IEA estimates that if no action is taken to improve energy efficiency in this sector, energy consumption in buildings will rise by almost 50% between Year 2010 and Year 2050. At the same time, an estimated 77% reduction in total CO_2emissions from the buildings sector is required by Year 2050 if the 2°C target is to be met, according to the IEA [1]. Thus, the buildings sector is considered a key sector for the changes needed to achieve the required emission reduction targets.

Nevertheless, the transformation of the buildings sector should not be treated as a separate, demand side-focused phenomenon. In its report, the IEA recognises the synergy between the buildings sector and the electric power sector. With over 50% of all globally consumed electricity being used in buildings, electricity savings in the buildings sector will result in: decreases in power generation (which is globally still dominated by fossil fuel-fired power plants); avoided capacity additions; and reductions in network expansion works. However, electricity is not the largest end-use in terms of final energy consumption in buildings. Space heating and hot-water use account for 79% of the total final energy use in EU households [2]. And while within the EU the heat market is mainly (around two-thirds) dominated by on-site boilers that are fed fossil fuels [3], 55% of space heating and hot-water load in Sweden is covered by District Heating (DH) systems [4]. In multi-dwelling buildings, this proportion reaches 92%. Considering these values, we can confidently claim that DH systems constitute a significant part of the total Swedish energy system.

As in the case of electric power systems, the main challenge for DH systems to contribute to meeting global environmental targets is altering the fuel mix. Even though approximately 90% of the total heat generated in Swedish DH systems is derived from the burning of biofuels and waste incineration, the units used for load following are often fossil fuel-fired Heat-only Boilers (HOBs), also called ‘peaking HOBs’. The operation of these fossil fuel-fired HOBs results in annual emissions of 2.75 $MtCO_2$ [5]. The use of peaking HOBs in DH systems is dictated by the varying heating load, which can fluctuate significantly even within a single day. Thus, one strategy to reduce the utilisation of fossil fuel-fired peaking HOBs, towards further decarbonising Swedish DH systems, is to make either heat generation or heating demand more flexible. One of the options to make heat generation more flexible is to integrate some form of energy storage, which can be controlled by a DH system operator together with other heat generation units, e.g., a hot-water tank or borehole geothermal energy storage. One of the ways to make the demand side more flexible is to activate Demand Response (DR) in buildings by, for example, allowing indoor temperature deviations from a set-point temperature. In this case, the buildings will be temporarily over-heated or under-heated, i.e., storing or releasing heat, and acting as a Thermal Energy Storage (TES) on the demand side. This approach emphasises that the linkage between DH systems and the buildings sector is not necessarily unidirectional, in that supply meets inelastic demand, but rather a complex interaction between the two components of the overall energy system.

Swedish DH systems are also of special interest with respect to their generation mix. In Year 2013, around 40% of the total heat generation in DHs was from Combined Heat and Power (CHP) plants and around 8% was from Heat Pumps (HPs) [6], using waste heat as the heating source (mainly sewage water). The utilisation of CHP plants (to generate electricity) and HPs (to consume electricity) in DH systems creates a strong linkage between the heat and electric power systems. There is considerable potential for flexibility services, which DH systems can provide via smart operation of CHP plants and HPs, that can facilitate the integration of variable renewable energy resources, i.e., solar and wind power, into the electric power system.

To summarise, the triple synergy between the largest heat supplier in Sweden (DH systems), the buildings sector, and the electric power sector warrants in-depth investigation in relation to global sustainable development.

1.1 Aim and scope of the thesis

This thesis attempts to elucidate how the interplay between the components of the energy system, namely buildings, DH systems, and the power sector, can facilitate its transition to a sustainable future. The main aim is to increase our understanding of how the future energy demand in buildings will take shape and how it can interact (influencing and being influenced) with the energy supply side. The present thesis focuses on the heating part of the energy supply and demand in buildings. Our over-arching hypothesis is that flexible and controllable heat demand from buildings can improve efficiency and help to decarbonise the heat supply side. The following questions are posed to test this hypothesis:

- What are the benefits (economic, technical and/or environmental) that can be derived from the integration of the flexible energy demand in buildings with the supply side – in our case DH systems?
- To what extent and in what way can the heating load and, correspondingly, the heat generation of a city change as a result of such an interplay between demand and supply?
- In what way does the impact of flexible demand on the heat supply side differ from that of centralised energy storage, e.g., a hot-water tank in a DH system?

To answer these question, it is crucial to understand in detail how centralised heat generation systems, i.e., DH, work. In addition to the heating load, electricity prices strongly influence the operation of DH systems via the operation of CHP plants and HPs. Thus, the following additional questions are addressed:

- In what ways do DH systems that are equipped with electricity price-sensitive technologies, i.e., CHP plants and HPs, interact with the power sector?
- What are the implications of a future with more-volatile electricity prices for the interplay between DH systems and the power sector?

The city of Gothenburg in Sweden is used as a case study in this work and in all the appended papers. The above-mentioned questions are tackled using techno-economic optimisation models. In **Papers II** and **III**, the system boundary is drawn around the heat supply side - the DH system of Gothenburg, which means that parameters such as electricity prices and system heating loads are given as inputs to the models. In **Paper I**, the system boundary is expanded to include the building stock of the city; therefore, the space heating demand from buildings is estimated together with the heat supply within the model.

1.2 Contributions of the thesis

Papers I and **II** study the interplay between DH systems and flexible space heating demand from buildings, using two methodologically different approaches. In **Paper II**, the flexibility of space heating demand is achieved by modelling the building stock connected to a DH system as a two-thermal-nodes energy storage system. Using this Building Inertia Thermal Energy Storage (BITES) system for storing and retrieving heat in/from buildings, controlled indoor temperature deviations from the reference set-point temperature (e.g., 21°C) can be achieved, i.e., DR takes place. In **Paper I**, the estimation of the space heating demand from buildings and the calculation of the optimal dispatch of heat generation units in a DH system are integrated into a single optimisation model. Thus, the space heating demand profile of buildings is constructed by taking into account the technical and economic parameters of the DH system. Application of the two methodological approaches allows us to improve the validity of our results.

In **Paper II**, the utilisation strategy and the impact of BITES are compared to the case in which TES, via a Hot Water Tank (HWT), is integrated into the DH system. This comparison of two TES types that are fundamentally different in nature (supply vs. demand side impacts), when applied to the same DH system and studied using the same modelling approach, is unique.

In the campaign towards a sustainable future with high penetration levels of variable renewables, the issues of variability and flexibility attain a high level of importance in the field of energy systems. Therefore, with the aim of studying the impacts of short-term (hourly) and long-term (seasonal) variations in electricity prices (**Paper III**) and heating demand (**Papers I** and **II**) on the operation of DH systems, a set of techno-economic optimisation models with a sufficient level of detail is developed and presented in this work.

1.3 Outline of the thesis

This thesis is based on the three appended papers and this extended summary. The extended summary consists of six chapters, with this *Introduction* being the first. Chapter 2 introduces some basic information and concepts that are relevant to this thesis and useful for readers who are not acquainted with the field. A brief literature review is also provided in Chapter 2. Chapter 3 describes the modelling approach and the assumptions that are applied in the appended papers. Chapter 4 presents and explains the input data used in the research. The main findings from the presented work are included in Chapter 5. Finally, Chapter 6 summarises the most important conclusions from the work and suggests some avenues of future research.

2. Background

This chapter gives a short introduction to the main concepts in focus in this thesis.

Basics of district heating systems

A DH system comprises a network of pipes that connect heat consumers, mainly residential and commercial buildings, with a number of centralised heat generation units. The overall objective of DH is to satisfy consumers' space heating and hot water demands. After heat is generated, it is distributed to the consumers in the form of steam (older systems), water or pressurised water via a network of insulated supply and return pipes, usually buried underground. The temperature of the water in the supply pipes of the existing DH systems is often <100°C, whereas recent developments tend towards "4th generation DH systems" with supply temperatures of 40°–50°C [7]. Generation mix of DH systems usually consists of HOBs, HPs, and electric heaters, which generate heat exclusively, and CHP plants, which are able to generate both heat and electricity. Modern DH systems can also accommodate units that use geothermal or solar energy for heat generation. Swedish DH systems, especially those in the large cities, are special in terms of their use of "recycled" heat (mainly associated with the use of industrial excess heat, flue gas condensation, and combustion of municipal and industrial waste). In Year 2015, the share of recycled heat from total heat deliveries by DH systems in Sweden was 32% [8].

DH systems have a number of advantages over individual heating systems. Centrally generated heat assures higher fuel efficiencies and, thereby, lower fuel consumption, as compared to decentralised heat generation. Furthermore, the co-generation of heat and electricity in CHP plants offsets electricity generation and carbon emissions from the electric power system. In addition, flue gas cleaning systems are more advanced and easier to install in larger combustion units than in individual boilers. Presently, DH systems are also considered to possess unused potential flexibility that can be of value not only in the DH systems themselves but can also provide service to the power sector [9]. However, these advantages come with a cost – investments in DH systems are significantly large and require a long-term financial commitment. Furthermore, due to losses that occur in the piping network, DH systems are less competitive in regions with low population (consumer) densities. Further insights into the technical, economic, environmental, market, and institutional contexts of DH both globally and, with a deeper analysis, in Europe can be found in the review of Werner [10].

"Demand" *vs.* "load"

In the literature, the terms *demand* and *load* in energy systems are often used interchangeably, yet, they are not equivalent in this thesis. Thus, in order to explain clearly the approach and assumptions applied in the appended papers and described in this thesis, the following assumptions are made to distinguish between these two terms.

In this thesis, the term *demand* indicates the amount of energy (heat) that is required or "wanted" by a consumer, e.g., in a building, in order to fulfil some need, e.g., maintaining the indoor temperature at a specified level. Thus, in the present work, the amount of heat required to maintain a pre-set indoor temperature in a building is calculated in terms of energy balances (for example, see **Paper I)** and is called the building space heating demand. In contrast, the term *load* indicates the amount of heat that is actually delivered to a consumer, e.g., a building. This means that if the demand is precisely fulfilled by the load, which is usually true for energy systems, the demand is equal to the load.

In this thesis, we attempt to close the energy balance at the system (city) level, i.e., the aggregated heat output from the heat generation units must satisfy the total system heating load. Therefore, the *total system heating load* is assumed to consist of the aggregated individual customer loads (e.g., building loads, loads from industrial users) plus distribution losses within the DH grid. In addition, in this thesis, it is assumed that the total system heating load corresponds to the aggregated heat output from the heat generation units available in the DH system.

Load variations and variation management

A common characteristic of energy (electric power and heating) systems is a demand-driven load that is not constant over time. Heating load variations in heating systems are characterised as seasonal or daily. Seasonal heating load variations are obvious, and arise from the requirement to maintain a constant indoor temperature in the connected buildings while the outdoor temperature changes significantly between seasons. In addition, seasonal differences in the heating load are dependent upon social factors: inhabitants usually stay indoors longer during the colder parts of the year and tend to increase their hot water use, as compared to the warmer months. Daily heating load variations, in turn, are driven by social factors to a greater extent than climatic factors, even though they are also influenced by, for example, day-night temperature differences. In residential buildings, the level of hot water use during the night-time is much lower than during the day-time, since the inhabitants are usually asleep at night. In addition, some people prefer to lower the indoor air temperature by a few degrees at night-time. As most commercial buildings are not in use during night-time, the ventilation rates and building temperatures are set lower. This behaviour significantly influences the levels of heat supplied to the customers over the course of a day, i.e., causes daily heating load variations.

Another feature of energy systems is that it is necessary to satisfy the aggregated load from all the customers using the available generation capacity at each instant in time. In terms of

DH systems, this requirement is crucial (albeit not as crucial as in the power system). If the level of heat generation in the system is lower than the total system heating load, the heat-consumers will be affected differently: the peripheral customers (the ones located farthest from the heat generation units) will experience a significant under-supply of heat, while the customers closer to the heat generators may not be affected at all. This is due to the pressure drop along the DH piping network that connects the customers. Therefore, variations in the heating load must be dealt meticulously by the generation capacities, in order to provide the same quality of heat supply to all the customers.

The varying heating load in heating systems can be met through two main strategies: (i) a supply side-oriented strategy that makes the heat generation more flexible; and (ii) a demand side-oriented strategy, whereby the heating demand becomes flexible. Historically, the most common solution has been to make the supply side flexible by installing so-called "load following" or "peaking" heat generation units. Peaking units are able to change their output in a flexible manner within a short time period, e.g., within minutes, albeit at the expense of higher running costs, as compared to those of base-load units. Thus, the more variations that a DH system experiences, the more peaking units are used and, as a result, the total cost of the heat deliveries increases. Considering that peaking units are mostly fossil fuel-fired, load variations also lead to higher CO_2 emissions associated with heat generation.

Another way to make heat generation more flexible is to add TES to the supply side. This option is associated with a number of advantages and disadvantages, with high investment cost being a serious disadvantage, as discussed in greater detail in the *Centralised thermal energy storage* section. As an alternative to supply-side TES, the thermal inertia of buildings connected to the heating system can be used for thermal storage. This alternative, which presumably requires significantly lower investment than a centralised TES, is discussed below in the *Demand response from space heating in buildings* section.

TES is a technology that stores thermal energy by heating or cooling a storage medium with the intention of using this energy subsequently for heating, cooling or electric power generation applications. TES systems can be classified as either centralised, e.g., a single standing borehole TES, or decentralised, e.g., a distributed piping network of a DH system. The implementation of TES in energy systems (at either the supply side or demand side) results in the TES acting as a buffer in the energy balance, thereby shifting the energy generation/demand from one period in time to another, e.g., supplying peak demand with the heat generated earlier during a period of low demand, which is referred to as *peak shaving* and *valley filling* (Fig.1). Peak shaving and valley filling result in a smoother overall load, and thus, increase the possibility to use baseload generation units with low running costs and decrease generation from costly peaking units.

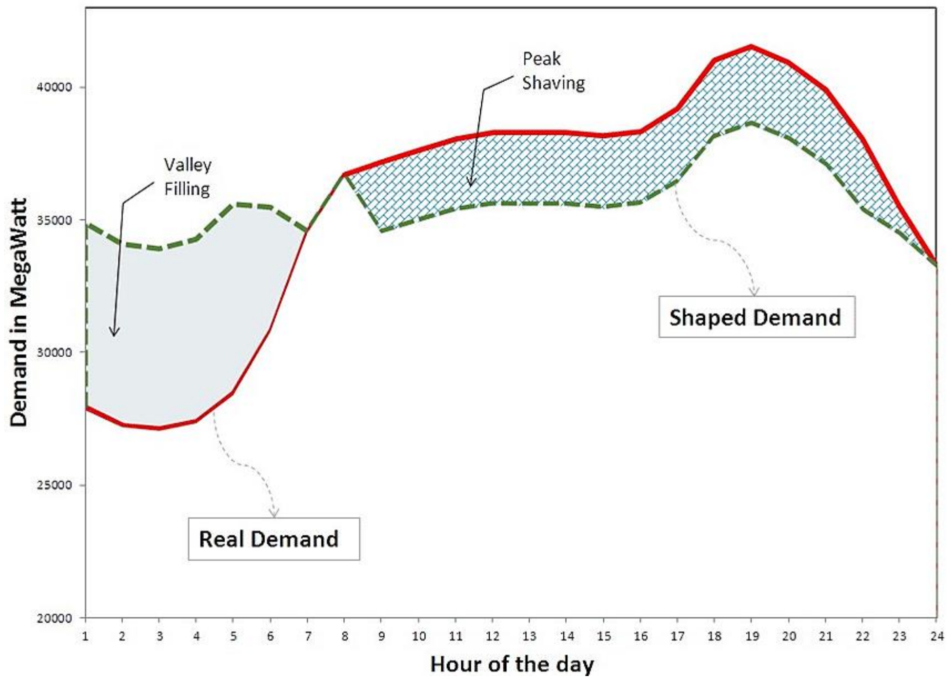

Fig.1. Schematic showing of peak shaving and valley filling in energy systems [11].

Centralised thermal energy storage

Centralised TES systems can be divided into three types: 1) sensible heat storage, in which thermal energy is stored by heating or cooling a liquid or solid storage medium (with water being the cheapest option); 2) latent heat storage using phase-change materials; and 3) thermo-chemical storage using chemical reactions to store and release thermal energy. Sensible TES in water, which is the option that is usually used for heating systems applications, is designed to be either short-term, i.e., daily or weekly, or seasonal, i.e., summer to winter (although to date, only a few units that store heat between seasons have been installed) storage.

In this work, we consider short-term HWT for applications in DH systems. HWTs are installed in a number of Scandinavian DH systems and are mainly used for two purposes: to decouple heat and power generation (since Scandinavian DH systems usually include CHP plants, as mentioned before); and for heating load variation management. In most of the applications, including the application considered in this work, HWT is based on a well-insulated, cylindrical water tank with a closed water circuit. This means that the hot water from the DH network is being injected/withdrawn directly at the top of the tank, while the cold water is added/withdrawn at the bottom of the tank. Water tanks that are used as HWT can have a volume of up to several thousand cubic meters and temperature ranges of 80°–90°C at the top of the tank and 20°–40°C at the bottom of the tank. The specific investment cost of HWTs ranges from 0.5 EUR/kWh to 3 EUR/kWh [12]. However, discussions with DH systems operators in Sweden reveal that the total cost of HWT installation and connection to the system may be double this estimated range.

Demand response from space heating in buildings

It has previously been stated that the alternative to flexible energy generation for load variation management is flexible energy demand. With respect to heating systems, flexible demand can be achieved by shifting in time the space heating demand or the hot water use in buildings. Since hot water use is mainly driven by social factors, which are assumed to be difficult to change, the greatest potential for ensuring demand flexibility in buildings lies in the space heating demand, assuming that small deviations of the indoor temperature are acceptable to the inhabitants.

At this point, the connections between the concepts of "flexible demand", "demand response" and "thermal energy storage" in buildings should be clarified. Throughout this thesis, it is assumed that the flexible space heating demand in buildings can be achieved by either allowing for DR in buildings (**Paper I**) or using the available building stock as a TES (**Paper II**). However, the guiding principle behind those two strategies for achieving flexible demand is the same: to increase the heat supply to buildings during the low-load hours (again, valley filling) in the DH system and to decrease the heat supply during the high-load hours (peak shaving), with negligible reduction in the customers' levels of heat comfort. In other words, the buildings that participate in DR in **Paper I** and the buildings used as TES in **Paper II** are temporarily and consecutively over-supplied and under-supplied with heat, resulting in indoor temperature deviations that lie within a temperature range that is acceptable to the inhabitants. Thus, the main difference between space heating DR and TES in buildings is the way in which they are modelled (for details, see Chapter 3), even though these two concepts are based on the same principle of using the thermal inertia of buildings for storing heat.

In general, DR provides an opportunity for the demand side to play an active role in the operation of energy systems by shifting or reducing its energy demand in response to some kind of incentive, e.g., a time-dependent price signal. As compared to centralised TES, the usage of buildings for load variation management has a number of advantages and disadvantages. The potential of a HWT can be limited by bottlenecks in the DH piping networks, while the buildings used for storing heat are dispersed and can be assumed to be available continuously to provide DR services. However, the use of buildings for TES entails organisational challenges. While HWT is assumed to be 100% owned and operated with the desired flexibility by the DH system operator, utilisation of buildings as TES relies on the establishment of a business that involves both the DH operator and house-owners, and this involves the installation of sufficient control systems. Furthermore, it also requires that indoor thermal comfort can be maintained at a level that is acceptable to the inhabitants/house-owners.

2.1 Related research

Even though DH is a well-established technology and has the potential to provide a number of benefits to the energy system, its development and role in future sustainable transitions are not obvious. For example, the Energy Roadmap 2050 [13] of Europe does not include DH as one of the key elements in its energy system development scenarios. Nevertheless, Connolly et al. [3] have claimed that with large-scale implementation of DH into the European energy system, the reductions in primary energy supplies and carbon emission reduction goals, as indicated in the Energy Roadmap, can be achieved at lower cost than in the scenarios without DH. The studies conducted by Lund et al. [7] and Persson et al. [14] indicate that DH and district cooling are important energy system components, that can facilitate reductions in primary energy consumption, increased energy efficiency, and the integration of renewable energy sources (RES).

As indicated previously, heating load variations directly affect the operation of DH systems and, therefore, have caught attention of other researchers in the past. A novel assessment method developed to describe relative daily variations has been presented by Gadd and Werner [15]. The method was applied to 20 Swedish DH systems, although it is generic in nature and can be applied to any system with daily variations. The method was additionally verified by studying the heating load variations in 141 DH substations [16]. Gadd and Werner conclude that there is no standard heating load pattern in DH substations (i.e., buildings connected to DH substations have very different heat consumption profiles), which implies that the scheduling of heat generation units in DH systems is a continuous and challenging process that requires sophisticated planning tools.

Computer-based techno-economic optimisation models are widely used to define the optimal composition and operation of district energy systems, including DH systems. A comprehensive review of the different optimisation techniques, as well as the optimisation tools used in district energy systems has been provided by Sameti and Haghighat [17]. In the studies of Mehleri at el. [18, 19], an optimisation model was developed to define the optimal district energy system components, as well as their optimal dispatch with the objective of minimising the annualised investment and running costs of the heat and electricity supplies in a small neighbourhood. Multi-objective optimisation models have been developed by Morvaj et al. [20] and Falke et al. [21] with the goal of studying the effects of different shares of RES in the electricity grid and the impacts of different energy-saving renovation measures in buildings, respectively, on the design and operation of district energy systems.

There are several studies that have modelled district energy systems with incorporated TES. The majority of these studies have focused on a centralised TES option (HWT). Bachmaier et al. [22] and Oluleye et al. [23] have used techno-economic models to design and optimise DH systems that contain TES units to improve the flexibility of CHP plants. Similarly, Chen et al.

[24], Yang et al. [25] and Fang et al. [26] have looked at the use of TES in conjunction with CHP plants to balance heat and electricity generation, with the overall aim of maximising the rate of wind power integration within the studied district energy systems. Wang et al. [27], Carpaneto et al. [28], Ameri et al. [29] and Buoro et al. [30] have used optimisation modelling to study the effects of integrating solar thermal plants together with thermal storage on heat and electricity generation in district energy systems. All these studied concluded that the availability of storage positively contributes to their objectives.

The DR potential of space heating demand in buildings have been studied by a number of researches, yet adopting different approaches. The most widely used approaches are the engineering bottom-up modelling of energy demand in buildings (used in **Paper I**) and the estimation and utilisation of the thermal storage potential of buildings conducting empirical tests (results of such approach were used in **Paper II**). A comprehensive review of the modelling techniques used for modelling energy consumption in the residential sector, including the description of and a number of examples of the engineering bottom-up modelling, has been conducted by Swan and Ugursal [31]. Hedegaard and Balyk [32] have used a building energy balance model in conjunction with an energy system dispatch model to study the DR potential of space heating demand and HPs in Danish single-family houses. They have concluded that the DR can effectively reduce the demand for peak capacity and, correspondingly, lead to savings in investments in new capacities. Another energy balance model has been developed by Halvgaard et al. [33] to study the potential of the thermal capacity of buildings to shift the energy consumption to low electricity-price periods through the use of HPs and floor heating. They report significant running cost savings, as compared to the reference operation strategies without any demand side management. The approach of estimating the potential of DR in buildings based on empirical tests can be exemplified by the works of Andersson and Werner [34] and Ingvarsson and Werner [35]. Both studies concluded that the thermal inertia of buildings can be effectively used for smoothing heat load variations, using the city of Gothenburg as a case study. The studies of Kensby [36, 37] provided an empirical test of the response of indoor temperature and heat load to different over-heating or under-heating patterns, concluding that multi-family residential buildings could be utilised as BITES with a capacity of 0.1 kWh/m^2 heated area, given the indoor temperature deviations from the set-point temperature do not exceed ±0.5°C.

3. Methods and Modelling

The objectives of the research listed in Section 1.1 are addressed by means of computer-based optimisation models. Three models, namely the Unit Commitment (UC) model, the Unit Commitment with Storage (UCS) model, and the Energy Balance Unit Commitment (EBUC) model, are developed and applied in the appended papers. The history of model development can be summarised as follows:

- The UC model is developed to identify the cost-optimal unit commitment and dispatch of heat generation units available in a DH system (**Paper III**)[1];
- The UCS model takes the UC model as the basis for further refinements to include and investigate the effects of incorporating TES into a DH system (**Paper II**); and
- The EBUC model is developed to integrate the UC model with a building physics energy balance model of a building stock, i.e., the EBUC model co-optimises the space heating demand in buildings with the dispatch of a DH system (**Paper I**).

Fig. **2** shows the relationships between the developed models and the specific models that are used in the indicated appended papers.

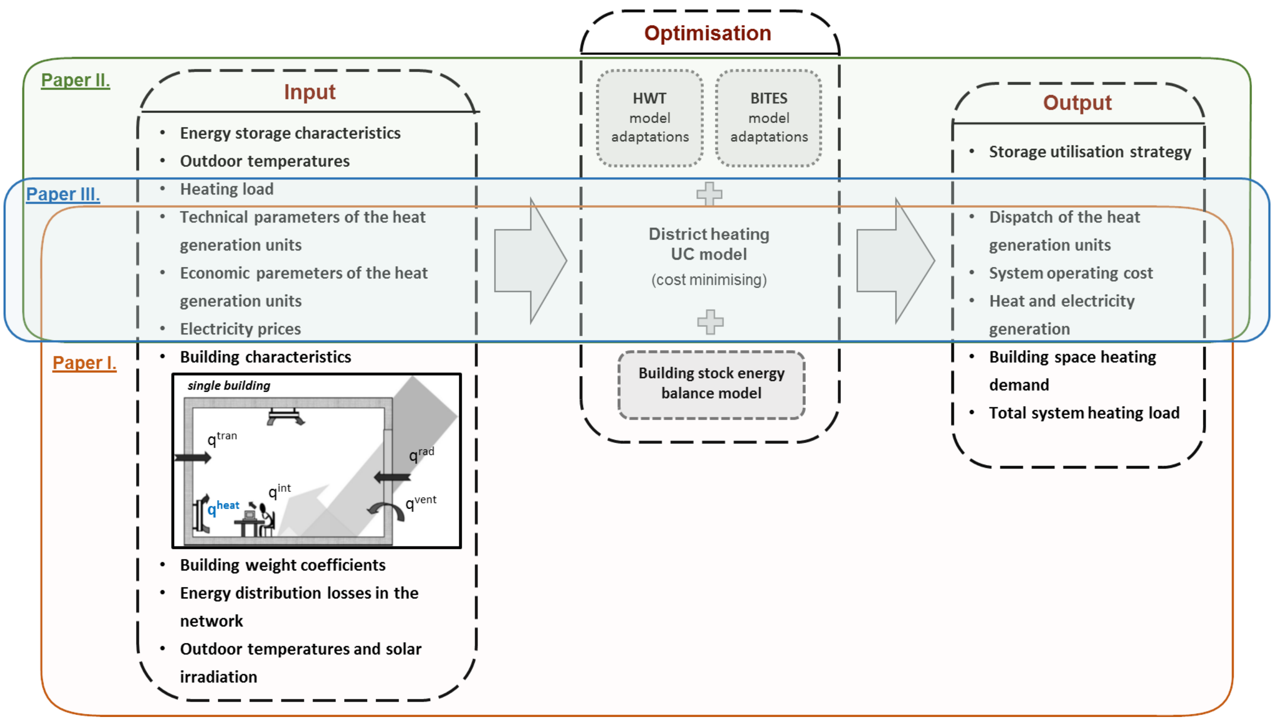

Fig. 2. Schematic of the connections between the optimisation models and the research described in the appended papers.

[1] In this Section appended papers appear in the order III, II and I due to the chronological and gradual development of the models (UC, UCS and EBUC) used in them.

The objective for all three models is to minimise the total yearly running cost of a DH system. The models are developed as mixed-integer linear optimisation problems with a time resolution of 1 hour and a time horizon of 1 year. All the models are deterministic, i.e., the input data are exogenously given in the form of parameters and the models have perfect foresight. The models are developed using the high-level modelling language GAMS [38].

3.1 Definitions and indicators

A few concepts and definitions need to be clarified before describing the methodology applied in the appended papers and the results achieved through the modelling.

Relative heat-load variations

As indicated in Section 1, one of the main challenges associated with the operation of DH systems is the variable, in both long-term (seasonal) and short-term (daily) respects, heating load. To describe the heat-load variations on different time-scales, the terms "relative daily load variations" (**RDLV**) [15] and "relative weekly load variations" (**RWLV**) are introduced. These terms are used in **Papers I** and **II** in the comparison of the effects of DR in buildings and availability of HWT on the total system heating load of the DH system.

RDLV and **RWLV** are defined as follows:

$$\boldsymbol{RDLV} = \frac{{}^{1}\!/_{2} \cdot \sum_{h=1}^{24} |Tot.Load_h - Tot.Load_d|}{Tot.Load_{yr} \cdot 24} \tag{1}$$

$$\boldsymbol{RWLV} = \frac{{}^{1}\!/_{2} \cdot \sum_{h=1}^{24\cdot 7} |Tot.Load_h - Tot.Load_w|}{Tot.Load_{yr} \cdot 24 \cdot 7} \tag{2}$$

where $Tot.Load_h$, $Tot.Load_d$, $Tot.Load_w$, and $Tot.Load_{yr}$ are the hourly and average daily, weekly, and yearly system heating loads of the city, respectively. The **RDLV** and **RWLV** values are determined for each day and for each week of the year, respectively, and quantify the amounts of heat that are averted from the daily average and weekly average heating loads. In other words, the **RDLV** and **RWLV** reflect the extents to which the hourly values of the heating load differ from the daily average and weekly average values, respectively.

3.2 Unit Commitment (UC) model

In **Paper III**, the effects of future fluctuating electricity prices on the operation of the DH system of Gothenburg, Sweden are studied. Furthermore, the types of benefits that the DH system can confer on the power sector, e.g., flexibility services, are also investigated. To address these questions, the UC model is developed with the main objective of defining the dispatch of heat generation units in the system that yields the lowest cost for heat deliveries, while taking into account the levels of electricity generated by CHP plants and consumed by HPs. To capture the short-term (hourly) variations in the electricity prices and the impacts of these prices on the dispatch of the DH system, a bottom-up engineering optimisation modelling is applied.

In the UC model, the description of the investigated DH system is limited to the technical and economic parameters of the available heat generation units (Table 1), while no characteristics of the piping network are considered. This is important to remember, as this approach does not account for any congestions that can occur in the network in reality. Furthermore, it is assumed that the DH system of Gothenburg has no connections to neighbouring DH systems. The parameters of the heat generation units, the applied electricity prices, and the heating load of the system are given as inputs to the UC model. Thus, the applied UC model investigates the operation of 20 heat generation units available in the system (some units are aggregated based on technology type or economic characteristics).

Table 1. The UC model input parameters that characterise the DH system of Gothenburg.

Description	*Units*
Max/min output limits of a heat generation unit	kWh/h
Ramp limits of a heat generation unit	kWh/h
Minimum up- and down-times of a heat generation unit	h
Efficiency of a heat generation unit	%
COP value for HPs	-
Power-to-heat ratio of CHP plants	-
Fuel cost for a heat generation unit	SEK/kWh
Variable O&M cost of a heat generation unit	SEK/kWh
Energy tax	SEK/kWh
Carbon dioxide tax	SEK/tCO2
Price of Electricity Certificates	SEK/kWh
Start-up cost of a heat generation unit	SEK

The mathematical formulae used and a detailed explanation of the UC model are available in **Paper III**, Appendix A. The UC model has been validated against real-life data from the operation of the DH system of Gothenburg.

3.3 Unit Commitment with Storage (UCS) model

In **Paper II**, the impact of TES on the operation of the DH system of Gothenburg is described. Two types of TES are chosen for the investigation: centralised HWT (TES via a hot water tank) and decentralised BITES (TES via thermal inertia of buildings). Since the two storage types are very different in nature – HWT is a supply-side buffer that helps heat generation units to maintain the balance between the supply and demand in every instant of time, while BITES alters the heating load itself (acts like a DR mechanism) – **Paper II** also investigates the principal differences in their utilisation patterns. To account for the utilisation of TES in the UCS model, the reference heat balance equation from the UC model is modified to allow it to supply and retrieve (i.e., charge and discharge) heat from/to the TES. Furthermore, each of the storage options is described in the UCS model using a set of equations that governs the amount of energy stored, the charge and discharge rates, and the energy losses to the surroundings. This approach allows for an objective comparison of BITES and HWT by modelling them in a similar fashion in the UCS model.

The principle of how BITES operates is based on temporal over-heating or under-heating of buildings. This means that only a super-positioned heating load associated with those temperature variations above and below the set-point temperature (i.e., heating load associated with the utilisation of buildings as TES) is modelled in the energy balance of the UCS model, with the heating load without any storage is used as a reference. The description of BITES in **Paper II** is based on the studies of Kensby et al. [36, 37] and Carlsson [39]. As a result of their work, 40% of all multi-family residential buildings in Gothenburg are represented in the UCS model as a BITES that consists of two thermal nodes. The two nodes represent the building envelope and the core, i.e., *deep* storage, as well as the indoor air and building internals (radiator system, furniture, outer layers of walls), i.e., *shallow* storage. The *deep* and *shallow* parts of the BITES, as modelled in the UCS model, are schematically shown in Fig. ***3***. The capacity of BITES is estimated by limiting the indoor temperature deviations in the investigated buildings to ±0.5°C. However, in **Paper II**, the assumption is made that only over-heating of buildings is allowed, i.e., a set-point indoor temperature corresponds to an empty BITES and over-heating of buildings corresponds to charging of the BITES. The charge and discharge rates of the *shallow* BITES (as this is the part of the BITES that is in contact with the DH network) are dependent upon the outdoor temperature. Energy losses from the shallow and deep parts of the BITES are assumed to decrease linearly with decreases in their respective charge levels.

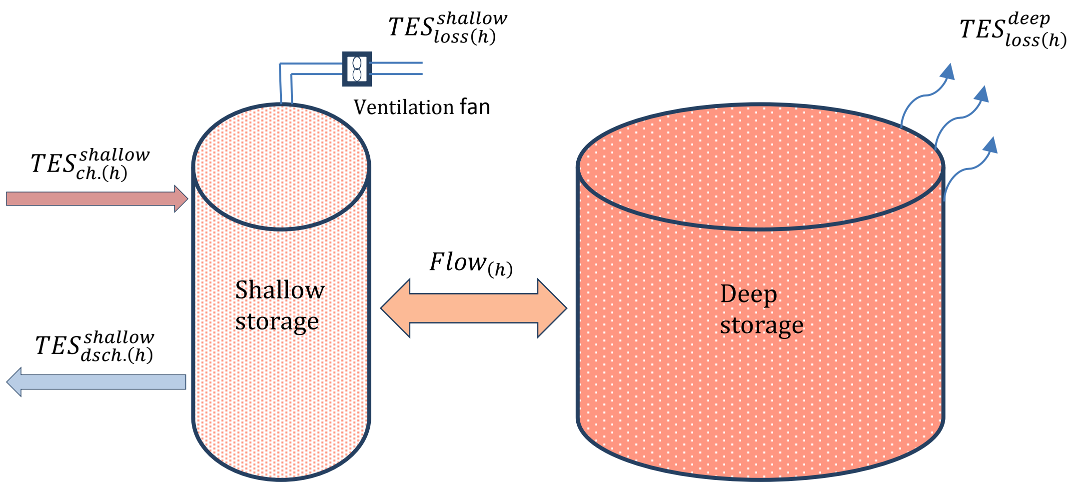

Fig. 3. Schematic of the shallow and deep components of the BITES, as modelled in the UCS model (**Paper II**).

HWT is modelled as a one-thermal-node storage system with the assumption that the water inside the tank is fully mixed, i.e., that the water temperature inside the tank is uniform. This simplification is justified by the findings of Steen et al. [40], which indicate that the energy losses from a fully mixed TES do not differ significantly from the losses estimated for a TES with ideal stratification (in reality, the stratification that occurs in tanks used as TES is not perfect, mainly due to mixing of the water during charge-discharge cycles). Energy losses from HWT are dependent upon both the amount of stored energy and the outdoor temperature.

A more detailed description of the two TES types investigated and the model adaptations introduced into the UCS model, as compared to the UC model, are given in **Paper II**.

3.4 Energy Balance Unit Commitment (EBUC) model

In **Paper I**, the potential effects of flexible heating demand in the building stock of Gothenburg on the total system heating load and the operation of the DH system are investigated. The DR is realised by allowing for indoor air-temperature variations, which was also the case for the estimation of the BITES capacity in **Paper II**. Thus, **Papers I** and **II** can be seen as addressing the same question as to "how DR via temperature variations in buildings influences the operation of DH systems". However, the modelling approach of the EBUC model is methodologically different from that of the UCS model, and it enhances our understanding of the factors that drive the actual demand, thereby raising new research questions associated with DR and/or efficiency measures in buildings.

The EBUC model was developed to integrate a bottom-up energy balance model, which calculates space heating demand in buildings, into the UC model. The energy balance model of buildings was originally created in the form of the Energy Carbon and Cost Assessment of Building Stocks (ECCABS) model by Mata et al. [41], and thereafter developed further by Nyholm et al. [42]. In brief, the energy balance model of buildings calculates the space heating demand from each modelled building based on its physical properties, climate conditions, and heating gains/losses that occur in the buildings (Table 2). Thus, when the energy balance model in buildings is integrated together with the UC model into the EBUC model, the dispatch of heat generation units in the DH model is co-optimised with the heating demand from the buildings. Furthermore, by allowing indoor temperature deviations within a predefined temperature span instead of a fixed set-point temperature requirement, the DR from the space heating in buildings is enabled. The main difference between the UCS (**Paper II)** and EBUC (**Paper I**) models is that the total system heating load is exogenously given to the UCS model as a single dataset of hourly values, whereas in the EBUC model the total heating load is disaggregated, i.e., the space heating demand from buildings is endogenously calculated within the model while other loads (i.e., hot-water load from buildings, industrial loads) are provided as inputs. A more detailed description of the modelling methodology and the EBUC model can be found in **Paper I**.

Importantly, in **Paper I**, the DR potential from the investigated building stock is limited by the assumption that the temperature of the buildings can only increase above the set-point requirement. This assumption reflects the cost-minimising nature of the EBUC model. If the temperature was allowed to drop below the set-point value, the model would obviously exploit this possibility to decrease the heat supply and, thereby, the total system running cost. While this would represent an energy-saving measure, the focus in the present work is on the DR potential.

It should also be noted that explicit modelling of every single building in the city is impossible due to a lack of data and the computational complexity of the model in this case. Thus, in the EBUC model, the building stock of Gothenburg is represented by a number of sample (representative) buildings. The calculated space heating demand for each of these sample buildings is then extrapolated to the total demand of the city's building stock through the application of building weight coefficients. The data that describe the building stock of Gothenburg are provided in Chapter 4, which also describes how the data were used. Using the described approach, the investigated building stock of Gothenburg is represented in the EBUC model by 134 sample buildings, which are scaled up, using the weight coefficients, to the calculated 18,600 existing buildings in the city. In addition, in order to speed up the calculations, the analysis in **Paper I** excludes the summer months (only the September-May period is modelled), since it is assumed that the space heating demand from buildings during the summer months is negligible.

Table 2. EBUC model input parameters that characterise the building stock of Gothenburg.

Description	*Units*
Total heated floor area of a building	m^2
Total area of the external surfaces of a building	m^2
Total area of the window surfaces of a building	m^2
Shading coefficient of windows	-
Frame coefficient of windows	-
Coefficient of solar transmission through windows	-
Average U-value of a building	$kW/m^2 \cdot ºC$
Thermal mass of the external thermal zone	kW/ºC
Thermal mass of the internal thermal zone	kW/ºC
Solar irradiation	kW/m^2
Outdoor temperature	ºC
Average constant values of the heat gains due to: - fan work, lighting, electrical appliances and occupants	kW/m^2
Hourly profiles of the heat gains due to: - fan work, lighting, electrical appliances and occupants	-
Efficiency of a heat recovery system (if available)	%

4. Input data

This chapter describes the data inputs used in this thesis and the appended papers. The City of Gothenburg, Sweden is taken as a case study in this work. Thus, the data concerning the investigated DH system, the building stock and the local weather conditions are descriptive for Gothenburg. The data concerning future electricity prices are descriptive for the south of Sweden, in which Gothenburg is located (further explained in Section 4.4 below). All the data in this thesis and the appended papers are for Year 2012, with the exception of the future electricity prices for Year 2030 used in **Paper III**.

4.1 District heating system

As indicated in Section 3.2, the description of the investigated DH system in the developed models is limited to the technical and economic parameters of the heat generation units. The technical parameters are mainly taken from the environmental reports (*miljörapporter*), issued yearly by the DH system operator and which describe the operation of the heat generation units over the year (exemplified by [43, 44]).

The economic parameters of the heat generation units are extracted from a number of governmental or scientific reports. The prices for wood chips, wood pellets and fuel oil are obtained from the Swedish Energy Agency [45]. The prices for bio oil and natural gas are assumed based on the data from purchase contracts. The energy and carbon taxes are taken from Nordenergi WG [46]. The price for Electricity Certificates, which are designed to support renewable electricity generation in the Nordic countries, is also extracted from the Swedish Energy Agency [47]. The data on the operation and maintenance costs of the units are taken from Goop [48].

All the technical and economic parameters of the heat generation units assumed in this work have been verified by the DH operator and can be found in **Paper III**.

4.2 Heating load

The data on the total system heating load, used as inputs in **Papers II** and **III**, were extracted from the real-life records of the operation of the investigated DH system. The total system heating load data set represents the aggregated heat generation from the heat generation units available in the system. However, as indicated earlier, the aggregated heat output from the generation units is assumed to be equal to the total system heating load, i.e., the level of heat generation meets the load requirement. The input hot-water and industrial heating loads applied in **Paper I**, are obtained by the disaggregation of the real-life measured generation in Year 2012.

4.3 Building stock

The data concerning the building stock of Gothenburg, as used in **Paper I**, are taken from the BETSI (*Byggnader Energi, Tekniska Status och Inomhusmiljö*) database [49]. The BETSI database contains detailed description of 1,800 buildings (1,400 residential and 400 non-residential), which were chosen by Boverket [50] and Statistics Sweden [51] as being representative of the Swedish building stock. Based on the building type, year of construction, location, and type of heating system, 134 representative buildings were extracted from BETSI and used in **Paper I** to represent the building stock connected to the DH system in Gothenburg. The building weight coefficients, i.e., coefficients used to scale up the chosen representative buildings to represent the total Swedish building stock, are also available in BETSI. The data on the number of dwellings in multi-family houses (available in [51]) and on the total heated floor area of multi-family houses and non-residential buildings in Gothenburg (available in Mangold et al. [52] and Swedish Energy Agency [53]) were used to recalculate the national building weight coefficients to match the number of buildings in Gothenburg. The weight coefficients for the single-family houses connected to the DH system of Gothenburg were not validated in the same way due to a lack of data.

The variations in the internal heat gains from lighting, appliances and occupants in the investigated buildings are given as inputs to the modelling. The variation profiles for single-family and multi-family houses are taken from the study of Nyholm et al. [54]. The variation profiles for non-residential buildings are extracted from the work of Grundsell [55].

4.4 Electricity prices

The data on the electricity prices used in **Papers I** and **II** are taken from the Nordic electricity wholesale market Nordpool [56] in the form of day-ahead electricity spot prices.

The future electricity price profiles used in **Paper III** are extracted from the ELIN-EPOD modelling package [57]. The ELIN model is an investment optimisation model that computes the development of the European (EU-27 Member States plus Switzerland and Norway) electricity system up to Year 2050. The ELIN model incorporates 50 price areas of the European electricity system and allows for electricity imports/exports between these areas. The ELIN model scenario results are then introduced to the dispatch EPOD model for further analysis at a higher time-resolution. The future electricity price profiles used in **Paper III** are generated by the ELIN-EPOD modelling package, assuming different penetration levels of wind and nuclear power in the national electricity system of Sweden in Year 2030. The electricity price profile for the reference Year 2012 is also modelled using the ELIN-EPOD package but using the recorded shares of wind and nuclear power in the system in Year 2012. The original datasets from the ELIN-EPOD modelling package have a 3-hour time resolution and are, therefore, converted to an hourly time resolution in **Paper III** by assigning the same price to every group of 3 hours.

The historical wholesale electricity price profile can be found in **Paper II**, Appendix A. The modelled electricity price profiles for Years 2012 and 2030 can be found in **Paper III**, Appendix B.

4.5 Weather data

Data for the outdoor air temperature are used in **Papers I** and **II**. The dataset consists of the hourly values averaged from the measurements collected by six temperature sensors located throughout the city of Gothenburg. In **Paper I**, these data are used for calculating the heat gains/losses in the investigated building stock due to air ventilation and energy transfer between the building structure and the surroundings. In **Paper II**, the outdoor air temperature is used to calculate the energy losses from the hot-water tank and to identify the maximum charge/discharge rates for BITES.

Solar irradiation data, which are used in **Paper I** for the calculation of the heat gains in the building stock due to solar irradiation, were obtained from the Swedish Meteorological and Hydrological Institute [58]. The dataset used shows the solar irradiance for the Nordic countries and has a spatial resolution of 11 × 11 km and a temporal resolution of 1 hour.

5. Results and Discussion

The most important findings from **Papers I–III** are presented in this chapter. First, the results cover the technical potential of the space heating DR in buildings and its impact on the heat generation in DH systems (**Paper I**). Second, the results from **Paper II** show how DR in buildings compares to a supply-side TES as a heat load variation management tool. Finally, the interplay between the heat generation in DH systems and the power sector is investigated (**Paper III**). The economic and environmental benefits of the studied synergies between the buildings, DH systems, and the power sector are also discussed.

5.1 Implications of the interplay between the flexible heating demand in buildings and the supply side

To study the potential of the DR in the building stock of Gothenburg to ease the requirement for ensuring instant demand/supply balance on the energy generation units, three scenarios were examined. The Reference, Tvar 1(C), and Tvar 3(C) scenarios are investigated in **Paper I**. In the Reference scenario, no DR is allowed in the investigated buildings, while in the Tvar 1(C) and Tvar 3(C) scenarios the DR is achieved through the possibility to increase the indoor temperature of the buildings above the set-point temperature (21°C for residential buildings and 20°C and 18°C for non-residential buildings) by 1°C and 3°C, respectively. It should be noted that in the Reference scenario, the indoor temperature is not prevented from rising above the set-point value owing to the influences of the outdoor air temperature, solar irradiation, and internal heat gains. Fig. ***4*** exemplifies the total system heating load of Gothenburg and the average indoor air temperature in the multi-family houses in March 2012, as obtained from the modelling of the investigated three scenarios. The indoor temperature variations in single-family houses and non-residential buildings followed the variations of the multi-family houses, so they are not shown.

Peak shaving and valley filling of the heating load

The results from the modelling in **Paper I** show that activated space heating DR in buildings can significantly affect the total system heating load of the city by smoothening its variations. From Fig. ***4*** it is clear that during the periods during which the heat generation in the Tvar 3(C) scenario exceeds the generation in the Reference scenario (indicated as valley filling), the indoor temperature in the investigated multi-family houses increases, i.e., the heat is stored. The stored heat is thereafter released to compensate for the gap between the heat generation in the Tvar 3(C) scenario and the Reference scenario (indicated as peak shaving), with a corresponding decrease in the indoor temperature of the buildings back to the 21°C level.

The total shifted space heating loads over the modelled period (a year without summer months) were 168 GWh and 186 GWh in the Tvar 1(C) and Tvar 3(C) scenarios, respectively. These values correspond to 5% and 6.5%, respectively, of the total yearly system load. The maximum space heating load shifted for the purpose of peak shaving was 235 MWh/h, which corresponds to 22% of the highest hourly heating load in the Reference scenario, and this occurred in the Tvar 3(C) scenario. The highest value of the shifted load for valley filling was 200 MWh/h in the same scenario. The corresponding values for load shifting for peak cutting and valley filling in the Tvar 1(C) scenario were 150 MWh/h and 180 MWh/h, respectively.

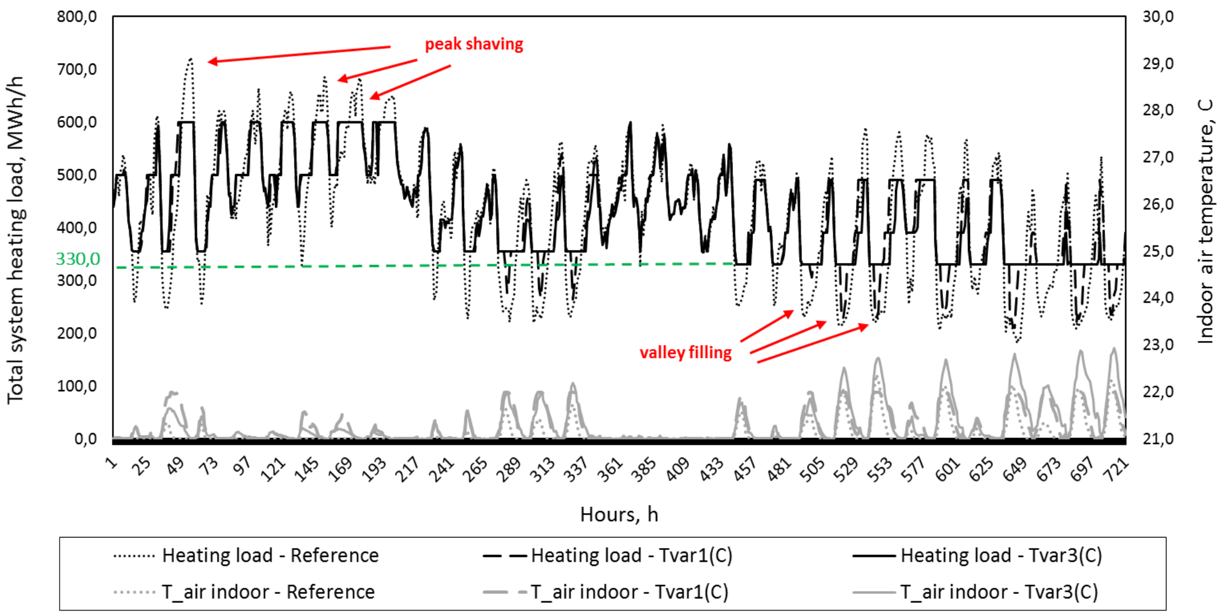

Fig. 4. Heating loads of the DH system of the City of Gothenburg and the average indoor air temperatures in the representative multi-family houses investigated, as obtained through EBUC modelling for March 2012 in the Reference, Tvar 1(C), and Tvar 3(C) scenarios.

Effects of DR on the system heat load variations

The extent to which the total system heating load was smoothened due to the active space heating DR in buildings was characterised with the aid of the indicator RDLV, presented in Fig. *5*. The results show that the DR achieved via increasing the indoor temperature by 3°C, i.e., the Tvar 3(C) scenario, smoothened the daily heat load variations to a greater degree than increasing the indoor temperature by 1°C, i.e., the sums of the RDLVs over the modelled period decreased by 20% and 30% in the Tvar 1(C) and Tvar 3(C) scenarios, respectively, as compared to the Reference scenario. However, the highest daily heat load variations, i.e., up to 18.5% in the Reference scenario, were smoothened to almost the same degree in the Tvar 1(C) scenario as in the Tvar 3(C) scenario. These results indicate diminishing returns in the case with 3°C over-heating as compared to the case with 1°C over-heating.

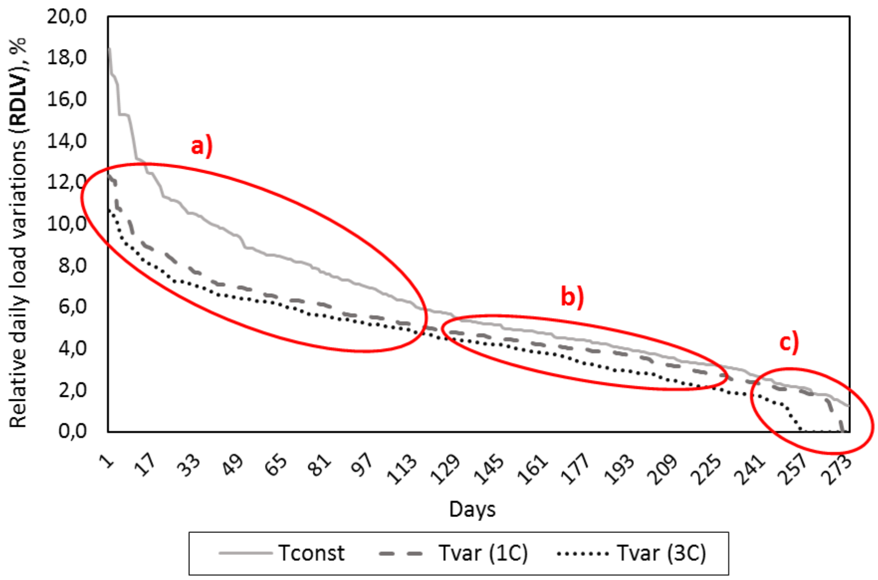

Fig. 5. The RDLVs for the investigated DH system of the City of Gothenburg, as obtained from the EBUC modelling for Year 2012 for the Reference, Tvar 1(C), and Tvar 3(C) scenarios (shown in descending order). Note that the modelled period is limited to 273 days, excluding the summer months, for computational reasons.

The results also show that the highest RDLVs in all the investigated scenarios occur during the spring-autumn months of the year (in Fig. ***5***, the RDLV values for the spring-autumn months are in area **a**). During the winter months, the heat load variations are lower (the RDLV values for winter months are in area **b** of Fig. ***5***). This is most likely due to more pronounced fluctuations in the daily outdoor temperatures and stronger solar irradiation during the spring-autumn seasons of the year, as compared to winter. It is also obvious from Fig. ***5*** that the DR obtained via both 1°C and 3°C of over-heating of the buildings decreases equally well the heat load variations in area **a** of Fig. ***5*** (again, the spring-autumn period). Whereas, in area **b** of Fig. ***5*** (winter period), the DR in the buildings has a weaker effect on the heat load variations. This can be explained by the fact that the outdoor temperatures during the winter months are low and cause higher energy losses from the buildings. Therefore, over-heating the buildings for the purposes of DR is not beneficial. In addition, the higher heating load during the colder winter months is mostly covered by the peaking HOBs, which are flexible and do not require much DR.

Area **c** in Fig. ***5*** shows that the space heating DR in the Tvar 3(C) scenario has sufficiently high capacity to flatten out some of the heat load variations over the period of a whole day. This phenomenon is also evident in Fig. ***4*** where the heat load remains at 330 MWh/h for a significant period of time, with the maximum period being almost 2 consecutive days. This constant heating load means that the generation of heat can be optimised more easily and scheduled to give the best economic and/or environmental performance. In the investigated DH system of Gothenburg, 330 MWh/h of heat is the aggregated output of the waste-heat technologies, i.e., technologies that make use of the waste heat from industries and municipal waste incineration. Thus, the space heating DR obtained via the +3°C indoor temperature deviations in the buildings connected to the DH system has the potential to increase noticeably the number of hours during which all the heat delivered to the customers in the city is generated from heating energy that otherwise would be wasted. Further implications of the DR for the heat generation in the investigated DH system are discussed below.

Effect of DR on the heat generation

The smoothening of the total system heating load of Gothenburg conferred by the flexible space heating demand in buildings has a significant impact on heat generation in the DH system. The main impacts of the DR on the DH system's operation are the increased heat supply from the base-load units and decreased heat generation from peaking HOBs.

Fig. ***6*** shows the number of start-ups for the small-scale gas-fired CHP plant, the HPs, and the peaking HOBs (aggregated) available in the DH system of Gothenburg, for the three scenarios investigated. The results indicate that allowing the indoor temperature in buildings to increase by 1°C (Tvar 1(C) scenario) results in a significant drop in the number of start-ups for the heat generation units. The largest decrease in the number of start-ups, by 85%, is registered for the peaking HOBs. However, as mentioned above, the additional effect of increasing by 3°C the permitted indoor-temperature deviations on the number of start-ups is weak, as can be seen in Fig. ***6*** (Tvar 3(C) scenario).

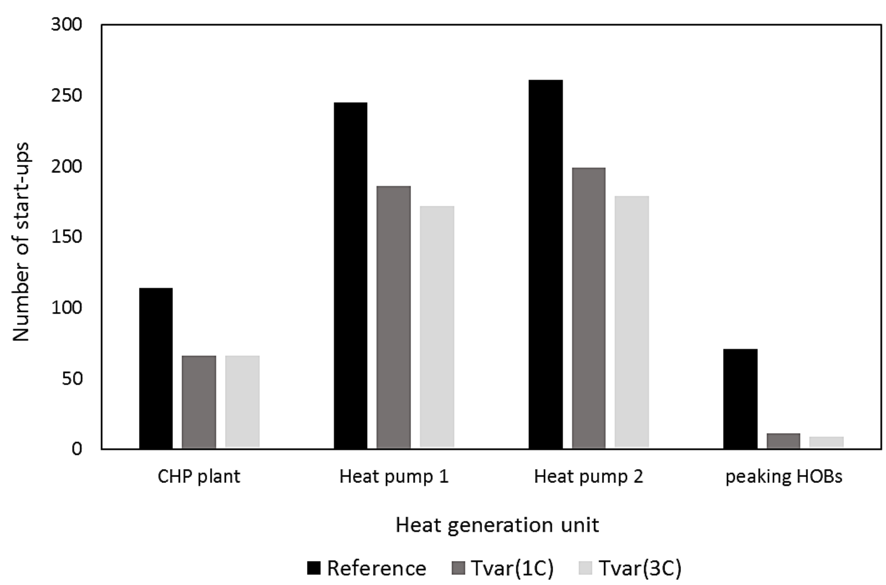

Fig. 6. Numbers of start-ups for the heat generation units in the DH system of Gothenburg, as obtained from the modelling for Year 2012 for the Reference, Tvar 1(C), and Tvar 3(C) scenarios. From **Paper I**.

The results also show that the levels of heat generation and the number of hours with maximum output increase for the waste-heat technologies. Considering that in all the investigated scenarios, the waste-heat technologies supply around 67% (almost 2,000 GWh) of the total system heating load, the increases in heat generation of 71 GWh and 69 GWh for the Tvar 1(C) and Tvar 3(C) scenarios, respectively, are small compared to the Reference scenario. However, the numbers of hours that these technologies deliver heat to the DH system at the maximum aggregated capacity (330 MWh/h) increase by 20% and 24% in the Tvar 1(C) and Tvar 3(C) scenarios, respectively, as compared to the Reference scenario. The increased heat supply from the waste-heat technologies leads to a decreased aggregated heat output from the dispatchable heat generation units (CHP plants, HPs, and HOBs) in the system. Furthermore, the results show that the number of hours that these dispatchable heat generators are in operation over the modelled period also decreases. However, the rate at which the number of operational hours decreases is higher than the rate at which the heat generation drops. This means that in the Tvar 1(C) and Tvar 3(C) scenarios, the heat generation units available in the DH system operate at an output level closer to the rated capacity more often over the year than is the case in the Reference scenario.

The operational changes that the DH system of Gothenburg undergoes due to the integration of flexible demand into the supply are associated with economic benefits. The modelling results indicate that the total yearly system running costs can be up to 4% and 6% lower in the Tvar 1(C) and Tvar 3(C) scenarios, respectively, as compared to the Reference scenario. Furthermore, more-stable operation in combination with a decreased number of start-ups of the heat generation units is likely to alleviate the control of the DH system from the operator's perspective and, potentially, decrease the wear on the equipment, thereby reducing the need for maintenance and repairs. This will extend the life-times of the units and lead to even greater savings. Finally, significantly reduced utilisation of the peaking HOBs, which at present are mainly gas- and oil-fired, will reduce the environmental footprint of the heat supply of the city.

5.2 Flexible heating demand *vs.* centralised TES in DH systems

The utilisation of centralised TESs in energy systems is another effective variation management strategy, as compared to flexible demand. **Paper II** compares the potential for heat load variation management and utilisation patterns of BITES (decentralised TES) and HWT (centralised TES) when integrated into the DH system of Gothenburg. Note that the flexibility of the space heating demand in buildings in **Paper II** is achieved by representing a part of the building stock of the city as BITES (from empirical studies), rather than the explicit modelling of the space heating demand used in **Paper I**. Thus, only 40% of the multi-family houses connected to the DH system of Gothenburg are investigated and compared to HWT in **Paper II**. Therefore, the modelling results presented in **Papers I** and **II** should be compared qualitatively rather than quantitatively.

Daily and weekly relative heat-load variations

The results from the modelling in **Paper II** confirm the findings described in **Paper I**, i.e., flexible demand that is achieved through controlled indoor temperature deviations in buildings influences the total system heating load by effectively smoothening its variations. However, the performance of HWT is superior because it can smoothen the load variations on longer time-scales, i.e., up to weekly load variations. Fig. *7* shows the RDLVs and RWLVs of the DH system of Gothenburg in those cases in which no storage (Reference scenario) and when either BITES or HWT, one at a time (BITES and HWT scenarios, respectively), is available in the DH system.

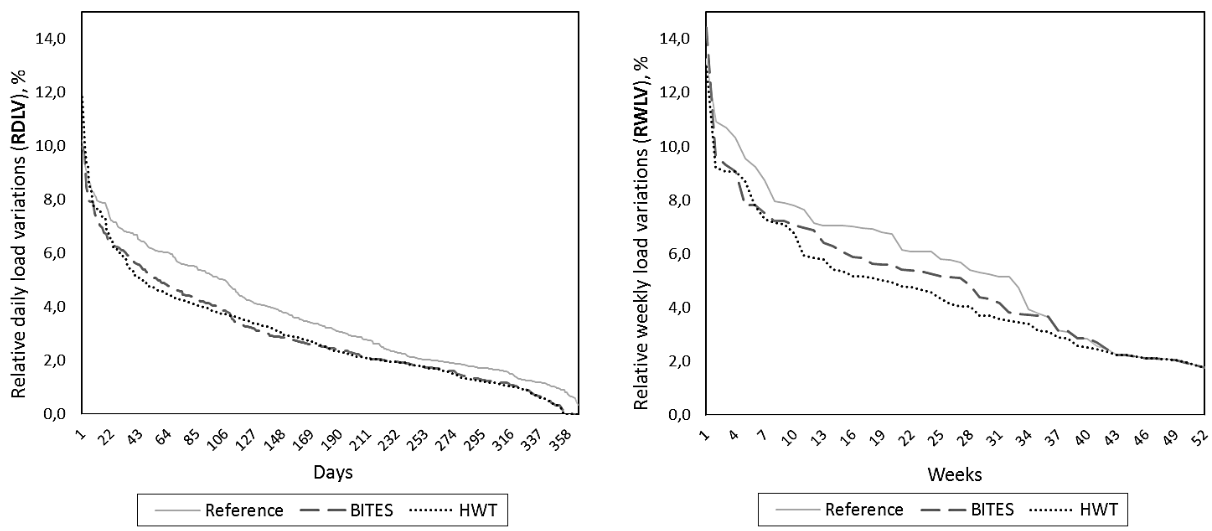

Fig. 7. The relative daily (RDLV) and weekly (RWLV) heat-load variations of the investigated DH system of Gothenburg for the Reference, BITES, and HWT scenarios, as obtained from the modelling (shown in descending order). From **Paper II**.

The results indicate that the two types of TES have similar effects on the short-term daily heat-load variations. Thus, the RDLVs decrease by around 20% in both the BITES and HWT scenarios, as compared to the Reference no-storage scenario. However, the RWLVs decrease by 10% and 17% in the BITES and the HWT scenarios, respectively, as compared to the Reference scenario. The greater ability of HWT to smoothen the weekly heat-load variations is attributed to its potential to store heat for longer periods of time (lower losses per hour), as compared to BITES. This is because the tanks used for HWT are specifically designed to store heat, which means that they are well-insulated and have low energy losses to the surroundings, while buildings obviously serve a different main purpose. These results also indicate that HWT has stronger potential than BITES to provide backup/redundancy to heat generation units on longer time-scales. Furthermore, the results show that in the HWT scenario, the heat generation units experience lower numbers of start-ups and an increased average hourly heat output, as compared to both the BITES and Reference scenarios.

It is also noteworthy from Fig. ***7*** that in both the BITES and HWT scenarios, the RWLV values never drop below 2%. This indicates that the capacity of either BITES or HWT is not sufficiently enough to flatten out the heating load of the investigated city of Gothenburg for 1 week or longer. If it becomes necessary to eliminate completely the weekly heat-load variations, one should consider the option of installing a larger TES unit, e.g., an underground geothermal borehole TES.

Utilisation patterns of BITES and HWT

In light of the presented findings on the smoothening effects of BITES and HWT, it is of importance to understand in which aspects the respective utilisation strategies of these two TES types differ from each other. The modelling results indicate that HWT is on average kept charged (stores heat) at a level that is more than double the level for BITES, i.e., the average energy levels of BITES and HWT over the modelled year are 270 MWh and 590 MWh, respectively. Furthermore, both BITES and HWT are equally adept at storing heat for short periods of time, i.e., up to 2 days, although if the heat is to be stored for a longer time, only HWT is suitable. This can be seen from Fig. ***8***, which shows the number of occasions during the modelled year on which BITES and HWT store ≥1,000 MWh of heat (50% of the maximum storage capacity) for the specified number of consecutive hours, which are aggregated into duration segments. It is clear that HWT is used 16 times to store ≥1,000 MWh of heat for periods longer than 50 consecutive hours, whereas BITES is used only 3 times (indicated by the red, dashed box in Fig. ***8***). These differences in heat storing patterns are attributed to the lower energy losses from HWT, as compared to BITES, and confer upon HWT a stronger potential to manage weekly heat-load variations, as indicated above.

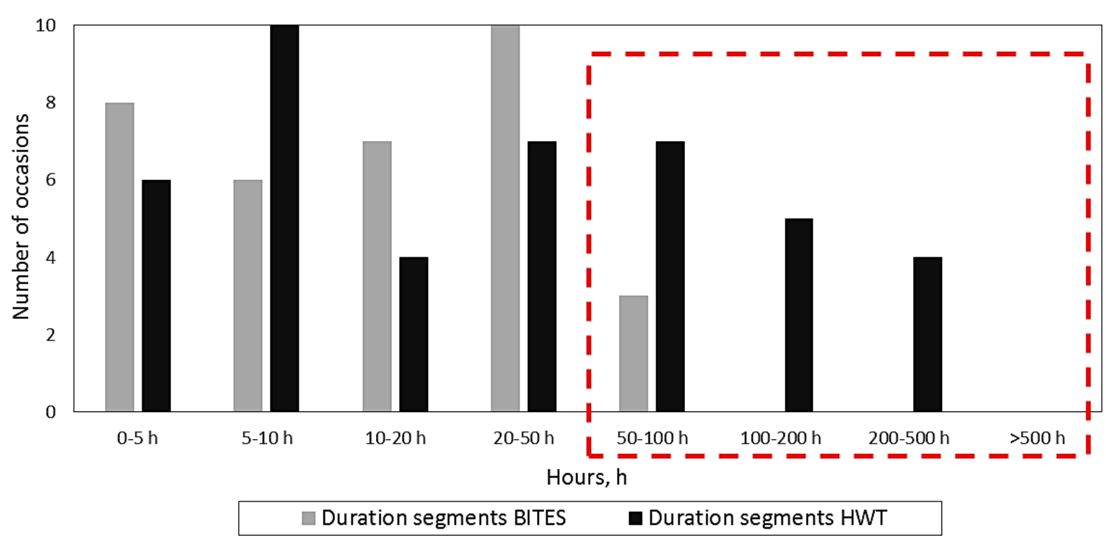

Fig. 8. Numbers of occasions (classified into duration segments) during which HWT and BITES remain charged at a level ≥1,000 MWh, as obtained from the UCS modelling. The red, dashed box highlights the stronger potential of HWT to store significant amounts of heat for longer periods of time than BITES. From **Paper II**.

In addition to the differences in energy storage level and duration, the two TES types differ in terms of their charge/discharge cycles. The results show that the charging patterns for both BITES and HWT are similar in terms of magnitude and time of occurrence, while the discharging patterns differ noticeably. HWT and BITES are being charged for around 2000 h over the course of a year (8760 h), with average charging rates of 43 MWh/h and 49 MWh/h, respectively. However, the discharging of BITES occurs for 4400 h, with an average discharge rate of 18 MWh/h, while HWT is discharged for only 2000 h, with an average discharge rate of 46 MWh/h (charge and discharge rates are specified taking into account the charge/discharge efficiencies). The main reason for this difference is the situation in which the shallow part of BITES is completely discharged, i.e., the indoor air and other building internals have reached the set-point indoor temperature, while the deep part of BITES is still charged, i.e., the temperature of the building envelope is still higher than the set-point temperature. Thus, discharge of BITES occurs at the rate of heat exchange between the building envelope and the indoor environment. These results indicate that HWT can be considered as a more flexible form of TES, as compared to BITES, since the capacity of the former is available in full for charging/discharging at any time-step, which should be beneficial for the DH system operator. This feature of HWT, together with the stronger potential to provide redundancy of heat generation units indicates a slight superiority for this type of TES in case the heating and electricity systems become more integrated, requiring a higher degree of flexibility of operation for DH systems.

Finally, the findings from **Paper II** indicate that the availability of TES in DH systems leads to economic benefits, i.e., a decreased total system running cost, as also observed in **Paper I**. The results indicate that the utilisation of BITES and HWT can lead to reductions of 1% and 2%, respectively, in the total system running cost of the DH system of Gothenburg, as compared to the case in which no TES is available. However, these cost reductions do not take into account the investment costs attributed to the TES types investigated. Rough estimations of the investment costs of BITES and HWT (for further details on the investment costs, see **Paper II**) indicate that the implementation of BITES can be several–fold cheaper than the implementation of HWT. Comparing the investment costs with the yearly savings in the system operating cost reveals that the implementation of BITES in the DH system investigated may have a payback period of as short as 1 year and up to 6 years, whereas the payback time for HWT is likely to exceed 10 years.

5.3 Interplay between DH systems and the power sector

Despite the benefits that DR in buildings and TES can provide to energy systems, their integration into the heating systems is not yet common practice. Meanwhile, the inter-linkage between DH systems and the power sector is already strong, especially in Scandinavia, where CHP plants and HPs are widely used for heat generation. With the rapid changes that the power sector will undergo (e.g., rising share of vRES), the price of electricity will most likely change in terms of both level and variability. In **Paper III**, the effects of present and future electricity prices, caused by the development of the power sector, on the operation of the DH system of Gothenburg are investigated. In addition, the potential of the DH system to provide flexibility services to the power sector is elaborated. Six scenarios are investigated and defined by different electricity price profiles, which are influenced by an increase in the wind power penetration level (from the current 5% to a future 50% penetration level) and the potential phasing out of nuclear power (the last scenario) from the Swedish power system. Further descriptions of the assumptions behind the scenarios can be found in **Paper III**.

The results from the modelling indicate that the dispatch of the investigated DH system and the individual operational strategies of CHP plants and HPs are affected by both the average electricity price and price fluctuations. In a future with a higher average electricity price and increased frequency of periods with high prices for electricity, as compared to current prices, the modelling results indicate that there will be up to 25% higher total yearly heat generation from CHP plants and up to 20% lower generation from HPs. The main reason for this is the change in the merit order of these two technologies during the periods with high electricity prices. CHP plants generate higher profits from sales of electricity at higher electricity prices, while HPs become more expensive to run. In contrast, during the periods with low prices for electricity, HPs are already used as base-load units, so an additional drop in the price will only reinforce their position. These results indicate that having both CHP plants and HPs in DH systems will be economically beneficial in a future with volatile electricity prices, since they will allow benefits to be accrued from both low and high electricity price periods.

The findings from **Paper III** indicate additional benefits of having in DH systems CHP plants that have the possibility to vary their power-to-heat ratio. CHP plants with variable power-to-heat ratios can benefit from operating in an ''electricity price-following" mode, in which electricity generation is prioritised over heat generation, during high-electricity-price periods. Fig. ***9***a shows the total yearly heat and electricity generation levels and the total numbers of operational hours for a gas-fired CHP plant with variable power-to-heat ratio available in the DH system of Gothenburg (RYA CHP plant) for all the investigated scenarios. In addition, Fig. ***9***b shows the operational modes of this unit in terms of the heat and electricity outputs for the scenario representing reference Year 2012. In the scenario with the most severely fluctuating electricity prices and the highest average electricity price ("50% wind no NUC" scenario), the number of hours during which that CHP plant prioritises electricity generation over heat generation and operates with the maximum possible electricity output (with electricity generation following the horizontal line in Fig. ***9***b) is double the number of hours during which the heat output is maximised. Furthermore, the heat output from that CHP plant increases by approximately 25%, whereas the electricity output is doubled compared to the other scenarios investigated.

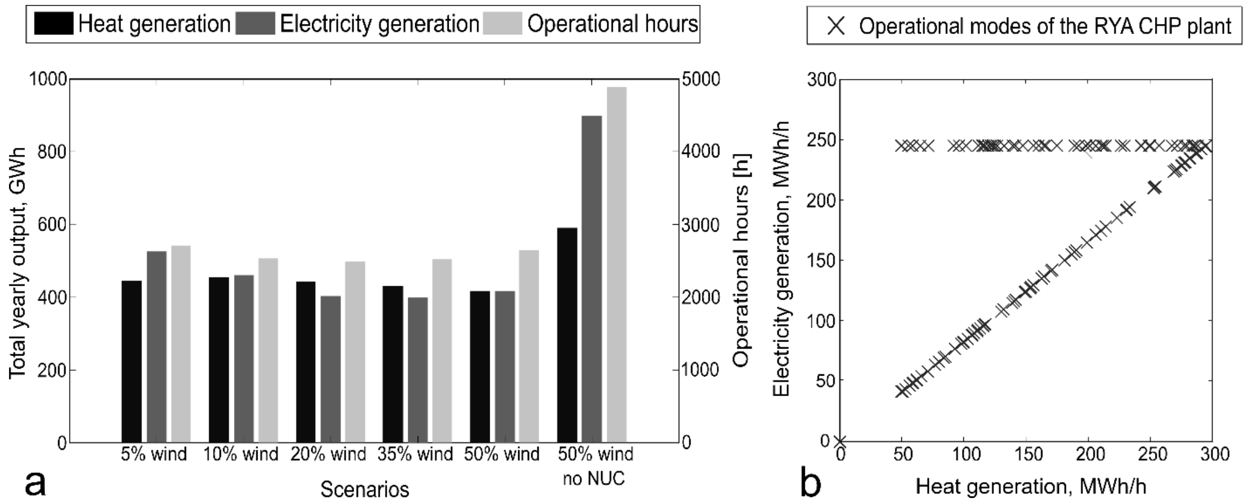

Fig. 9. The relationship between heat and electricity generation in a gas-fired CHP plant with variable power-to-heat ratio. a) The total yearly heat and electricity generation together with the total number of operational hours, as obtained from the modelling of six investigated scenarios. b) The operational modes, representing the heat generation and respective electricity generation levels, as obtained from the modelling of the scenario for Year 2012. From **Paper III**.

To summarise, the modelling results from **Paper III** indicate that the operation of DH systems will most likely be significantly affected by variations in the electricity price profiles. However, the outcomes from these changes could be beneficial both to the DH system owners and to the power system operators. The DH owners may benefit by making extra profit from providing flexibility services to the power sector via the smart dispatch and operation of their CHP and HP capacities. The power sector, on the other hand, can benefit from having an additional, rather reliable, in contrast to, for example, DR from electric space heating in buildings, provider of flexibility services. This is because the business model of DH systems is profit-driven, i.e., power system operators are likely to increase electricity generation when the price is high and to decrease it when the price is low, whereas the potential of DR from electric space heating can be restricted by the preferences of the inhabitants. Thus, the possibility exists to provide dispatchable electricity generation and consumption from DH, which can facilitate the integration of vRES in the power sector.

6. Conclusions

At the beginning of this thesis, the question was posed as to whether the synergies between the building sector, DH systems, and the power sector have the potential to facilitate the required transition of the energy system to a sustainable future. A simple answer to this question based on the results of this work is "yes" – the integration of flexible and controllable DR from space heating demand in buildings can improve efficiency and cost effectiveness and, at least in the case of the studied city of Gothenburg, can reduce the carbon footprint of the heat supply, while flexible heat generation in DH systems is shown to be a valuable provider of flexibility services for the power sector.

From the modelling results presented here, it is clear that if the space heating DR in buildings is realised, through permitting indoor temperature deviations from the set-point temperature, it could have a significant impact on the total system heating load of the city. Both methodological approaches used in this work, i.e., heat supply optimisation modelling with integrated DR via explicit calculation of the space heating demand and representation of the building stock as a TES, indicate that the main outcome from having flexible heating demand in buildings is effective smoothening of the total system heating load. Smoothening is defined here as decreases in the number and amplitude of the heat-load variations. The results indicate that the possibility to control the indoor temperature deviations by as little as +1°C from the set-point value (21°C, 20°C, and 18°C depending on the building type) can lead to a 20% decrease in the sum of the RDLVs over a year. Furthermore, we show that the DR in buildings is most effective during the period when daily heat-load variations are greatest, i.e., during the spring and autumn months.

The results of this work further reveal that using the thermal inertia of buildings as a heat storage system is as effective at reducing the daily heat-load variations as a centralised HWT. However, if the goal is to moderate the heat-load variations on a longer time-scale, e.g., weekly variations, storage in HWT is superior (due to the lower energy losses). Moreover, HWT is considered to be the more-flexible heat storage option because it is not limited by an additional heat exchange stage, as is the heat storage in buildings, i.e., heat exchange between the building envelope and the internals. However, our analysis indicates that the cost of investment in HWT may be up to 10-times higher than the cost required to achieve controlled space heating DR in buildings.

The modelling results obtained in this work show that the flattening of the total system heating load, derived from both space heating DR activation and utilisation of a centralised HWT, results in more-efficient heat generation. We show that the heat supply from base-load units increases, while the output from peaking HOBs decreases in all the investigated scenarios with storage (in buildings or in the water tank) available in the system. Our results reveal that the DR achieved via 1°C over-heating of buildings can lead to an 85% decrease in the number of starts and stops of the peaking, fossil-fired heat generators available in the investigated DH system. These results imply that the available peaking capacities can be used much less (and, therefore, some of them can be retired), so as to avoid costly investments in new peaking HOBs in the future. Furthermore, the DR achieved via 3°C over-heating results in a noticeable increase in the number of hours during which the total system heating load of the city is supplied entirely by technologies that use excess heat energy from industry, which otherwise would be wasted. Following these changes in the heat generation strategies, we observe a decrease in the total running cost of the investigated DH system, with the largest drop of 6% appearing in the case with the 3°C over-heating-based DR, as compared to the current mode of system operation.

Finally, the synergy between DH systems and the power sector is shown to be mutually beneficial. Smarter, flexible utilisation of CHP plants and HPs could bring additional economic benefits to DH systems operators by increasing the electricity generation during periods of high electricity prices (usually corresponding to periods with low generation from vRES) and by decreasing generation when the price is low (periods with excess generation from vRES). Simultaneously, the flexibility services that are provided by DH systems could help to accommodate more vRES within the power system.

Future Research

In this thesis, a common method of assessing the DR potential from space heating demand in buildings by allowing only for upward variations from a set-point temperature is applied. However, other methods can be used to assess the energy flexibility of buildings, as reviewed by Lopes et al. [59]. One such method, which allows for both downward and upward variations of the temperature around the set-point temperature, yet having a cost that depends on the degree of the deviation, was applied in the study of Nyholm et al. [60] to study the DR potential of electric space heating in Swedish single-family houses. They concluded that the method with both upward and downward temperature variations has a lower intensity of DR dispatch and lower absolute variations in indoor temperature, as compared to the method of only upward temperature deviations, providing the same economic benefits to the energy system. Therefore, a potential future research objective will be to investigate the DR potential of buildings connected to DH systems using the method of both up- and down-ward temperature variations around the set-point value.

Another issue that would be interesting to address is the representation of hot-water demand in investigated buildings. A common practice is to treat the demand for hot water as a single stream, as is the case in this thesis, since space heating still represents the main energy demand in buildings. However, with more low-energy buildings being constructed and connected to DH systems, the share of hot-water demand increases in the total energy consumption profile of buildings. Therefore, characterisation and explicit modelling of the various end-uses of hot water in buildings might reveal new insights into the energy consumption in buildings and potential DR strategies derived from hot-water demand.

This thesis presents research that is focused on the current building stock and the DH system of Gothenburg. However, to attain European energy efficiency standards, the majority of the existing buildings should be renovated and energy retrofitted. While there are many different energy-saving measures and packages of energy-saving measures available for implementation, it is not yet clear to what extents and in what ways they will influence the heating load, and correspondingly, heat generation, if implemented. Therefore, it would be of value to study the effects of energy conservation measures, both for space heating and hot-water demand, applied to the existing building stock with an additional focus on the interplay between the supply and demand sides.

Further, scaling up the presented research to the national level is a future research ambition. Finally, expanding the currently heat-oriented research to the total energy (heat and electricity) use and investigating the future energy load curve in buildings is the overall goal of my research.

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