

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Decentralization in the electricity system:

At the household, community and city levels

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CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2019

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Printed by Chalmers Reproservice

Gothenburg, Sweden 2019

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### ABSTRACT

Recent years have seen a rise in the number of implementations of small-scale generation and storage technologies for electricity and heat at different levels in the energy system. This trend towards decentralization of the system is driven by rapid decrease in technology costs, as well as the intentions expressed by various stakeholders to contribute to a carbon-neutral energy system. This thesis investigates the investments and operation of generation and storage technologies at three levels within the energy system: i) residential *Prosumer households*, which use photovoltaic (PV)-battery systems to supply and shift their electricity demand; ii) *Prosumer communities*, in which prosumer households share electricity; and iii) *Smart integrated cities*, which make use of interconnections between the electricity, heating, and transport sectors.

Three techno-economic optimization modeling methods are utilized to study technology investment and dispatch, self-consumption of electricity and heat at different levels of decentralization, and the interactions that occur between decentralized systems and the centralized electricity system. Prosumer households are modeled by combining a household electricity cost optimization model and a northern European electricity system dispatch model. The optimization model developed to study prosumer communities directly compares the PV-battery system investments and operations in individual prosumer households and in prosumer households within a community. The city energy system optimization model is designed to analyze interconnections between the urban electricity and heat (and in future work, also transport) sectors.

It is shown that prosumer households under the current Swedish tariff system experience a strong incentive to self-consume PV-generated electricity within their households and experience a weak incentive to operate their battery systems such as to reduce operational costs within the electricity system. Being part of a prosumer community can provide the highest monetary benefit to prosumer households for the purpose of reducing the connection capacity to the centralized system. Prosumer communities exhibit different patterns of electricity trade to the centralized system than individual prosumer households, due to local balancing of electricity within the community. On the city level, the installation of local generation and storage technologies for electricity and heat can reduce the stress on the connection to the centralized electricity system. Thus, local electricity generation can help to meet increases in electricity demand and demand peaks at the city level, stemming from city growth or electrification of energy use within the city. An interaction between the electricity and heating sectors in the city energy system can in the modeling results be seen in, for example, the utilization of power-to-heat technologies, which often use electricity during low-cost hours. Storage systems for electricity and heat are utilized within the city to shift electricity and heat between different periods.

**Keywords:** *Decentralization, Prosumers, Community energy, Smart city, Storage systems, Photovoltaic, Power-to-heat, Energy system modeling, Optimization*



## ACKNOWLEDGMENTS

I would like to thank my supervisors Filip Johnsson, Mikael Odenberger and Lisa Göransson for their guidance and support throughout this work. Filip, thank you for your valuable input, helping me to put my work into perspective and always taking the time to give feedback on writing publications. Mikael, thank you for your energy in all our discussions and for not letting me forget the link between my research and reality. And thank you to Lisa for adapting to all circumstances, keeping up the positivity and always having an idea on how to work around modelling problems.

The financial support for this work comes from the Swedish Energy Agency within the scope of Graduate School in Energy Systems.

I am grateful for all my amazing, current and former, colleagues here at Energiteknik; work becomes so much easier when there are also ice cream and board game breaks. Thank you to those of you who always have open ears and office doors. Thank you to the A-team for all the help with practical issues that show up during PhD student life. Emil, thank you for not only sharing an office with me but also so much of your time and experience.

A big thanks also to Therese at feelgood, for the amazing help I got there; anxiety and stress related to work and how we can deal with it is something we all should be more open to talk about.

Thank you to my friends for all the moral support and the hours of games, hiking and all the things that take my mind off work sometimes. To my family in Austria, thank you for supporting all my choices, even when they lead me to cold and foreign countries, and for letting me know that there's a place where I am always welcome to come back to. To my Swedish family, thank you for your part in making me feel at home here. Robin, thank you for taking on all of life's adventures together, I love you!

*Verena Heinisch,*

Göteborg, October 2019



## LIST OF PUBLICATIONS

The thesis is based on the following publications, which are referred to in the text according to their Roman numerals:

- I. Heinisch V, Odenberger M, Göransson L, Johnsson F. *Prosumers in the Electricity System— Household vs. System Optimization of the Operation of Residential Photovoltaic Battery Systems*. *Front Energy Res* 2019;6. doi:10.3389/fenrg.2018.00145.
- II. Heinisch V, Odenberger M, Göransson L, Johnsson F. *Organizing prosumers into electricity trading communities: Costs to attain electricity transfer limitations and self-sufficiency goals*. *Int J Energy Res* 2019;er.4720. doi:10.1002/er.4720.
- III. Heinisch V, Göransson L, Odenberger M, Johnsson F. *Interconnection of the electricity and heating sectors to support the energy transition in cities*. Accepted for publication in the EERA JP Smart Cities Special Issue series ISSUE 2/2019. Special issue on Tools, technologies and systems integration for the Smart and Sustainable Cities to come. *Int J Sustain Energy Plan Manag* 2019;24 2019. <http://dx.doi.org/10.5278/ijsepm.3328>.

### **Authors' contributions:**

Verena Heinisch is the principal author of **Papers I–III** and performed the modeling and analysis for all three papers. Filip Johnsson and Mikael Odenberger contributed with editing and discussion to **Papers I–III**. Lisa Göransson contributed to the method development in **Papers II** and **III**, as well as with editing and discussion for all three research papers.



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# 1. INTRODUCTION

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*The urgency of taking action against climate change and for the transition to a low-carbon energy system has reached different actors and stakeholders in society. The awareness and interest in creating change and to adapt are found at various structural levels, e.g., private homeowners generating and storing their own electricity and aiming for self-sufficiency, local politicians formulating urban sustainability goals and directing developments towards smart integrated cities, as well as at the national, European and global levels. This thesis investigates the techno-economic values of and incentives for adapting low-carbon energy technologies at different levels of decentralization in the energy system, ranging from households to communities to the smart integrated city.*

Technological innovations and the rapid decrease in cost of photovoltaic (PV) panels, battery storage systems, wind turbines, and communication technologies have noticeably changed the developmental path of the energy system over the last decade [1]. For various actors, there is now the possibility to assume active control of their energy utilization behaviors, leading to an inherently more complex energy system that requires different management and control strategies [2]. The emergence of new technologies for energy supply, storage, and control also enables multiple actions to mitigate the effects of climate change. Contribution to a fossil-free energy system is one of the main drivers for the growing number of energy technology installations on the decentralized level [3]. In order to achieve net-zero emissions in all parts of the system, future energy systems will likely have to be integrated and interconnected across sectors, as well as from supply to demand [4,5].

This thesis investigates three levels of decentralization in the energy system in: (i) so-called *prosumer households* that have small-scale technologies for the generation and storage of electricity installed, which means that they not only consume but also produce electricity; (ii) *prosumer communities*, within which several prosumer households collectively manage their energy utilization; and (iii) *Smart integrated cities*, which are prepared for challenges related to increased urbanization and climate change, implementing interconnections between the electricity, heating and transport sectors.

## 1.1. AIMS AND SCOPE

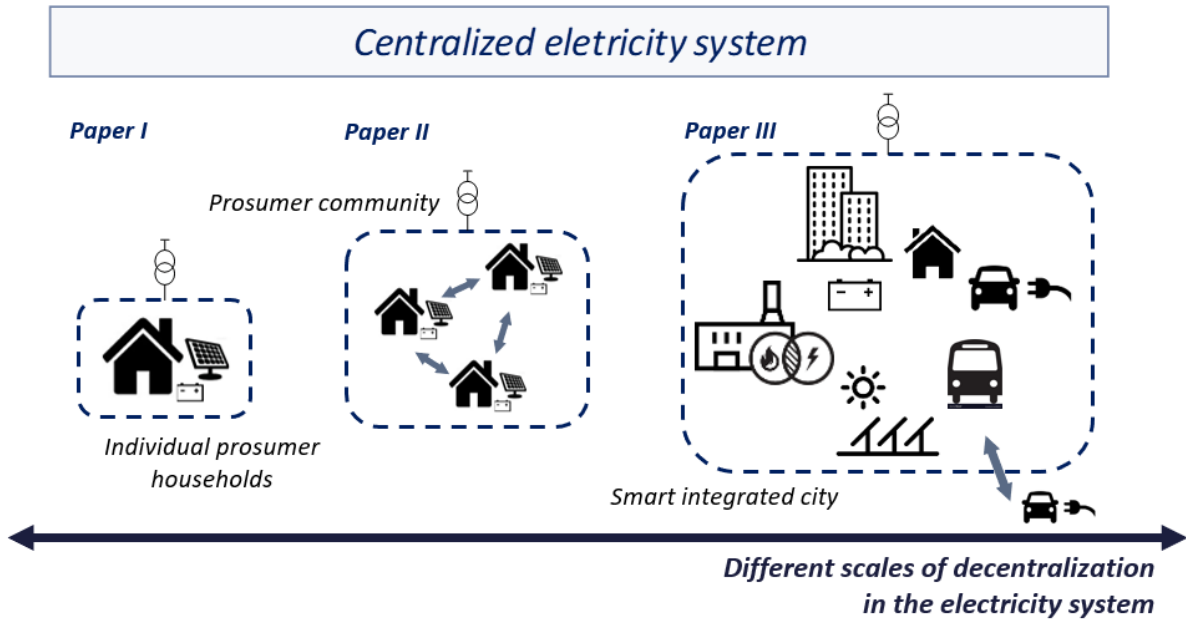
The main focus of this thesis is the roles that electricity and heat generation and storage technologies play in the different levels of decentralization within the energy system. The overall goal is to provide methods and outcomes linked to the techno-economic factors that influence the adoption of distributed low-carbon technologies at different levels within the energy system, and to provide insights into the factors that shape the interactions between the decentralized systems and the national centralized electricity and energy systems. More specifically, this thesis aims to:

- i. Develop modeling methods that enable the identification of the **techno-economic parameters** that affect investment decisions and the hourly operation of electricity and heat technologies on different structural levels, i.e., individual prosumer households, prosumer communities, and smart integrated cities.
- ii. Analyze how local generation and storage technologies are utilized for the purposes of **self-consumption and local energy balancing** in prosumer households, prosumer communities, and the urban energy system.
- iii. Investigate the **interactions between decentralized electricity systems and the centralized electricity system** and the national power grid, where the decentralized systems are studied at the levels of prosumer households, prosumer communities, and the urban energy system. Trading patterns and the utilization of the connection capacity to the central grid are investigated.

The thesis consists of this introductory essay and three appended papers. **Papers I and II** focus exclusively on electricity, whereas **Paper III** considers the interactions between the electricity and district heating systems in a model that can include the transport sector in future work.

## 1.2. CONTRIBUTION OF THE THESIS

The work presented in this thesis contributes to understanding the roles of decentralization at different levels within the energy system, as illustrated in **Figure 1**. **Paper I** analyzes individual prosumer households within the centralized Nordic electricity system. **Paper II** compares prosumer communities to individual prosumer households. **Paper III** focuses on the synergies between the electricity and heating systems in smart integrated cities. There may be different incentives for introducing decentralization at different levels in the energy systems, as different actors are involved in the decision-making process. The methods used in this thesis allows one to draw conclusions from the modeling work performed at three different levels in the energy system.



**Figure 1: Schematic of the different levels of decentralization within the electricity system that are considered in this thesis (including the integration of the district heating system on the city level)**

**Paper I** estimates the value of residential household PV-battery systems, comparing the optimal operation from the perspectives of individual households and the Nordic electricity system. This paper resolves whether incentives given to prosumer households align with optimal electricity system dispatch, and it analyses the optimal battery system dispatch from both the prosumer household and electricity system perspectives.

**Paper II** develops and applies a model of PV-battery system investment and operation to prosumer electricity trading communities. The study compares individual prosumer households to prosumer electricity trading communities where the purpose is to increase electricity self-sufficiency and reduce dependence on the grid operator.

**Paper III** presents the first step in the development of a model to study the sectoral integration of energy systems on city level. The paper introduces an optimization model that can be used to study flexibility in the electricity, heating and transport sectors on city level and presents details regarding the interactions that occur between the electricity and heating systems, as applied to a case study of the city of Gothenburg, Sweden.

The following sections provide background information on the decentralized energy systems and the different levels therein, i.e., prosumer households, prosumer communities, and smart integrated cities, considered in this work (Chapter 2), present the modeling methods and input data used (Chapter 3), and summarize and discuss the main findings (Chapter 4). The conclusions are presented in Chapter 5, and this is followed by proposals for further research questions (Chapter 6).



## 2. BACKGROUND AND RELATED WORK

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*In the transition to a climate-neutral energy system, renewable energy sources and energy storage systems are likely to play significant roles. They are technologies that are scalable and that can, together with the availability of information and communication technologies, lay the foundation for a gradual shift from a purely centralized electricity system to a system in which distributed generation and storage technologies for electricity and heat, and sectoral integration on a decentralized level become more prominent.*

Historically, the European electricity system has been dominated by large-scale power plants and extensive transmission grids, with one-directional power flow from generation to demand centers. Distributed technologies and increasing decentralization have the potential to disrupt this system. However, the extents to which electricity generation will occur at different levels in the system and how these levels can provide flexibility are currently unclear.

### ***Terminology: Distributed and decentralized***

The terms *distributed* and *decentralized* are sometimes used interchangeably in the literature. Distributed electricity generation and storage technologies are generally defined as being small-scale and connected to the distribution grid or ‘behind the meter’ at a customer site [6]. Commonly used terms in the literature include distributed generation (DG) and distributed energy resources (DER) [3]. In this thesis, the term *decentralized* will mainly be used as the direct opposite of the *centralized* electricity and energy systems. Thus, distributed generation and storage technologies are important components of the decentralization of the energy system. Here, the term *decentralized* also reflects a clear focus on local energy balancing (which is not inherently captured by the term *distributed technologies*), as it involves the local integration of energy system sectors and energy carriers.

The term *local energy balancing*, as used in this work, describes the utilization of distributed technologies, so as to meet the local demand for energy services by local generation, given a certain criterion such as minimizing the total costs of investment and operation in the local energy system.

In the literature, the characteristics and possible integration of centralized and decentralized energy systems are discussed. Funke and Bauknecht [7] have developed a framework to describe and compare centralized and decentralized electricity systems, based on the dimensions of infrastructure location (entailing the connectivity and proximity of generation units) and infrastructure operation (entailing flexibility and controllability). McKenna [5] has outlined the characteristics of centralized and decentralized energy systems, while also including the topics of economics of scale and social acceptance related to these two systems. Mehigan et al. [3] have discussed the role of distributed generation (DG) within centralized systems. Amongst the factors that influence the role of DG within a centralized electricity system, the authors have identified as important the potential for DG to be integrated into the existing infrastructure and the possibility for further developments to integrate DG

with the transport and heating sectors, as well as regulatory factors that affect the emergence and operation of DG. Mehigan et al. [3] have also discussed the requirements and challenges related to the modeling tools needed to capture most of the factors that influence decentralization within the future electricity system. **Table 1** provides a summary of the characteristics for centralized and decentralized energy systems based on the previous studies [3,5,7].

**Table 1: Descriptions and characteristics of centralized and decentralized energy systems. Sources: [3,5,7].**

	<b>Centralized energy systems</b>	<b>Decentralized energy systems</b>
<b>Structure</b>	Mostly one-directional power flow: <ul style="list-style-type: none"> <li>- <i>Generation, demand, transmission/distribution</i></li> </ul>	Integrated: <ul style="list-style-type: none"> <li>- <i>Vertically (voltage levels)</i></li> <li>- <i>Horizontally (energy carriers)</i></li> </ul>
<b>Generation</b>	Few large power plants, <ul style="list-style-type: none"> <li>- <i>Mostly connected to transmission grid</i></li> <li>- <i>Located near resources/supply</i></li> </ul>	Many small power plants <ul style="list-style-type: none"> <li>- <i>Mostly connected to distribution grid</i></li> <li>- <i>Located near load/demand</i></li> </ul>
<b>Flexibility</b>	On larger scale: <ul style="list-style-type: none"> <li>- <i>Transmission grid, covering large geographic areas</i></li> <li>- <i>Load management from large consumers</i></li> <li>- <i>Large-scale storage systems</i></li> </ul>	On smaller scale: <ul style="list-style-type: none"> <li>- <i>Distribution grid, smaller geographic areas</i></li> <li>- <i>Load management from many small customers</i></li> <li>- <i>Dependent on information and communication technologies</i></li> <li>- <i>Small-scale storage systems</i></li> </ul>
<b>Markets</b>	Centralized markets	Central and local markets <ul style="list-style-type: none"> <li>- <i>Aggregators, virtual power plants, prosumers, energy communities</i></li> </ul>
<b>Actors</b>	Few large companies	Many small actors/local actors
<b>Cost structures</b>	Economies of scale	Many different owners/investors
<b>Social factors</b>	Social acceptance of large-scale construction projects uncertain	Consumer motivation and engagement with technologies uncertain

To determine the extents to which and ways in which decentralization can and should be integrated into the European energy system, different values and trade-offs should be evaluated. Decentralization is not only able to improve the vertical integration of power systems, i.e., between supply and demand and between different voltage levels, but can also facilitate horizontal integration between different sectors in the energy system and different energy carriers [5]. Sectoral integration has been identified as an important measure to adopt climate-neutral energy carriers in different sectors of the energy system [4,8]. Balancing and control in decentralized systems, including the implementation of information and communication technologies, can facilitate this progress. Burger et al. [9] have argued that the locational value that decentralized technologies can deliver (to avoid network upgrades or high network losses in some areas) should be weighed against the economics of scale when employing larger-scale units, so as to maximize social welfare. Markets and regulations should ideally capture this locational value by using price signals as incentives. Decisions concerning investments in and the

operation of small-scale energy technologies, as well as energy planning are today taken at different levels. The following sections give an overview of the research on decentralized energy systems on the three different levels upon which this thesis focuses, i.e. prosumer households, prosumer communities, and smart integrated cities (see also **Figure 1**).

## 2.1. PROSUMERS OF ELECTRICITY – AT THE HOUSEHOLD LEVEL

The smallest scale for decentralized energy technologies considered in this thesis is the prosumer household. One of the enabling forces for households to initiate the generation and storage of electricity is the decreasing costs of technologies that generate and store electricity on a small scale. The IEA [10] lists four different factors that incentivize consumers of electricity to become prosumers: a) *economic* drivers, including technology costs, level of retail electricity prices etc.; b) *behavioral* drivers, including the desire for energy autonomy or to contribute to a more climate-friendly electricity supply; c) *technological* drivers, which could accelerate prosumer growth, such as electric vehicles or demand-side management; and d) *national conditions*, including the space available for PV and electric grid setups.

### **Terminology: Prosumers of electricity**

While there is no formal definition of the term *prosumer* in the context of electricity systems, the most widely utilized description is of the prosumer as a user of electricity who not only consumes but also produces electricity [1,11,12]. This description often includes the electricity storage behind the meter that enables the prosumer to defer the usage of electricity to a later time-point. Prosumers of electricity can be completely energy-independent, so-called 'off-grid' prosumers, but are in many cases still connected to the centralized electricity system and alter their electricity load through the utilization of decentralized technologies.

While this definition is applicable to all the different kinds of electricity use (at industrial and commercial sites, in apartment blocks, etc.), the focus of the present work is on residential prosumer households.

### **2.1.1. Decentralized generation and storage in prosumer households**

Technologies that are suitable for use in residential prosumer households include PV and battery systems, as well as heating technologies, such as heat pumps and in some countries, micro CHP (combined heat and power) units [13]. In the upcoming years, adoption of electric vehicles in prosumer households can be expected to increase, possibly contributing additional electricity storage within prosumer systems. Previous studies have investigated the economic advantages that may accrue to the prosumer household from utilizing PV-battery systems [12,14–18], as well as the potential to increase household self-sufficiency through in-house generation and storage systems [14,19–22]. There are also studies in the literature on the impacts that tariffs and retail pricing schemes will have on the profitability of prosumer-owned electricity generation and storage technologies and the patterns in which they are operated by the prosumer households [23,24]. In general, a distinction can be made between volumetric tariffs, whereby households pay per kWh that they consume, and capacity-based tariffs, whereby households are charged based on the peak demand capacity in kW

[25]. (Currently in many countries, customers pay a fixed charge depending on the connection capacity, independent of how many times a year the full capacity is actually used). While a variable, time-dependent capacity-based tariff system incentivizes prosumer households to avoid peaks in the purchase or feed-in of electricity, volumetric or energy-based tariffs tend to foster prosumer self-consumption. Time-dependent tariffs, wherein the charges to prosumers vary, e.g., during peak and off-peak periods or via dynamic pricing that follows the wholesale electricity price, encourage an electricity consumption behavior among prosumers, which is more in line with the operation of the centralized system. Hybrid tariffs with energy-based and capacity-based components are possible.

#### ***Terminology: Self-consumption and self-sufficiency***

The definitions of *self-sufficiency* and *self-consumption* outlined by Luthander et al. [19] are used for the work in this thesis. In the presence of local electricity generation, e.g., solar PV at the household level, and storage technologies, customers can choose among different options for meeting the in-house demand: either locally generated electricity or electricity from the grid. Therefore, *self-sufficiency* describes the share of electricity demand that can be supplied by locally generated electricity. *Self-consumption* is the share of the local electricity generation that is utilized locally (the remainder is either exported to the grid or not utilized, i.e., curtailed). In addition, the term 'energy autarky' has been used in the literature to describe local electricity generation and consumption [26].

#### **2.1.2. Prosumer households in the centralized electricity system**

Prosumer households that are not completely off-grid interact with the centralized electricity system. Owing to the utilization of local generation and storage technologies, this interaction with the centralized system is different from that experienced by pure consumers of electricity. Residential consumers' patterns of electricity purchase are directly related to their patterns of electricity usage, often with peaks in the mornings and evenings. Prosumers typically purchase less electricity due to their in-house generation and the purchase patterns are altered due to the presence of storage systems. In addition, feed-back of electricity from prosumer households to the centralized system is possible. When prosumers are numerous, this change in electricity load profiles has the potential to disrupt and severely affect the operation of the electricity system in its current form [27]. Modeling studies carried out by Schill et al. [28] and Günther et al. [29] have examined residential prosumer households as part of the power system, with a research focus similar to that of the study in **Paper I** of this thesis. Those groups have identified a clear incentive for self-consumption in prosumer households in the German system, and they highlight the close relationship between the type of prosumer tariff scheme used and the effects on the centralized system of the emergence of prosumers. Another study conducted by Klein et al. [30] has applied a market alignment indicator to describe how closely prosumer-controlled dispatch of battery systems resembles a dispatch that is solely steered by marked signals, and they have concluded that currently distributed energy resources in Germany are not operated in a system-optimal fashion. Klein et al. [30] have also highlighted that adaption of retail electricity prices does not have a significant impact on PV-battery system affordability.

While the impact of a change in prosumer load profiles can be both beneficial and challenging to the centralized system, a clear advantage associated with the increased usage of prosumer PV-battery systems is the activation of private capital for the purpose of energy system transition towards renewable resources [25].

## 2.2. PROSUMER COMMUNITIES, PROSUMER-TO-PROSUMER TRADING

With an increasing share of prosumers of electricity and decentralized generation and storage systems, an organized and structured integration of these developments into the existing electricity system is advantageous [11,31]. Some previous studies have focused on the development of local, prosumer or peer-to-peer trading markets [32–34], while others have focused on energy communities and neighborhood energy systems for the purpose of local energy autarky [26,35–37] or local involvement in the energy transition process [38,39]. Factors that prompt consumers to take part in community energy systems that have been mentioned in the literature [39,40] include: lack of confidence in the ability of governmental/regional strategies to meet environmental targets; a desire for independence from energy companies; the possibility to share costs and risks through co-ownership within a community; and high retail prices for electricity. A comprehensive review of the key issues and actors in energy communities has been given by Koirala et al. [41].

The techno-economic aspects of local energy balancing within a community or neighborhood system can be found in the literature under the term *Community energy storage* [42–46]. Similar to electricity generation and storage on the prosumer household level, community-level storage and generation can be utilized for local self-consumption, so as to adapt the purchase of electricity to hourly variable prices or to provide demand-side flexibility and reduce peaks in consumer electricity loads [43–45]. The ability to share electricity amongst the participants in the community means that an aggregating effect can be exploited and higher levels of self-sufficiency and self-consumption can be realized for lower levels of generation and storage capacity within the community, as described in Barbour et al. [46], McKenna et al. [26], and **Paper II** of this thesis.

The European Union has acknowledged the role of small-scale consumers of electricity and energy communities within the so-called *Clean Energy Package* [47–49]. In the framework, the European Commission defines terms such as the ‘renewable self-consumer’ and ‘renewable energy communities’, giving the topic visibility at the European level, and also acknowledges the opportunities for small-scale actors to act on energy markets.

The focus on prosumer communities in this thesis is linked to electricity as an energy carrier and the operation of PV-battery systems. Nonetheless, the community and neighborhood scale can serve as a basis for multi-energy systems that also involve heating, gas or hydrogen systems, as described in the literature on energy hubs [50,51] or energy clusters [36]. Storage systems for both electricity and heat can play an important role [52], and also private vehicles can be integrated into a multi-energy community system [53].

Similar to the individual prosumer households (described in Chapter 2.1.2), local energy communities can alter their interactions with the centralized energy system as compared to their present energy consumption pattern. While the centralized system is forced to adapt to this change, local energy balancing in prosumer communities can also be of benefit and supply flexibility and grid services, given a functioning coordination setup between the community and the centralized system [31,40].

### 2.3. SMART AND INTEGRATED CITIES

On the prosumer household and prosumer community levels, the adoption of electricity generation and storage technologies can largely be attributed to reduced technology costs and an increased willingness among private actors to contribute to an energy transition through choices regarding their energy consumption, as discussed above. In contrast, urban areas and cities, the third level of decentralization studied in this thesis, are faced with unavoidable political and technological challenges to ensure future growth and attractiveness. On the political side, cities often formulate strategies for complying with energy and climate targets communicated from the European and national levels [54,55]. On the technical side, cities are faced with the strong likelihood of increased electrification of sectors and processes that are currently supplied by fossil fuels. Together with increased city growth and urbanization [56], increases in the annual and peak electricity demands of cities can be expected, forcing cities to adapt. As a consequence, several cities have identified the need to increase the electricity connection capacity from the centralized electricity system [57], in projects that are often associated with long lead-times. In some Swedish cities, there are already capacity limitations in the electricity supply to the cities, which has hindered the establishment of new industries, such as computer server halls. An alternative or complement strategy to expanding the transmission capacity into the cities is local energy balancing, electricity generation and storage within the city boundaries, and synergies with other sectors, such as heating and transport, as analyzed with the model developed for **Paper III** of this thesis.

It has been argued by Cajot et al. [58] that the complexity of urban energy planning requires not only the expertise of urban actors and planners, but also contributions from quantitative methods, such as optimization methods. Reviews of modeling methods for urban energy systems in the different categories have been provided by Keirstead et al. [59] and Allegrini et al. [60]. Previous studies of the different areas within urban energy system modeling have covered: the integration of renewable energy sources [61–63]; the spatial and temporal distributions of energy consumption and supply within cities [64,65]; the operation of urban heating systems [66–68]; the optimal, low-carbon energy technology portfolio in the form of case studies [69–71]; the tools that can be used by the different urban stakeholders [72,73]; and the integration of electrified transport into the city's energy system [74,75].

The concept of *Smart cities* relates to the sectoral integration of energy, waste and mobility [76,77]. Given that integration is aiming for positive developments related to the climate, environment, and social and economic sectors, an important aspect of smart cities is the communication pathways and connections between these different areas. Calvillo et al. [77] have identified within a smart city the following five main energy-related intervention areas: generation, storage, infrastructure, facilities, and transport. The modeling presented in **Paper III** takes the initial steps towards developing an optimization model for investigating the effects of interconnecting the electricity, heating, and transport sectors in cities. The modeling method can be utilized to study the operation and value of local energy measures, such as local generation and storage of electricity and heat, including technologies that connect these two sectors (e.g., heat pumps or electric boilers) and in a later stage of the modeling development, the charging patterns of electrified vehicles.

### 3. MODELING AND INPUT DATA

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Three different optimization modeling packages have been applied in this thesis to investigate the three different levels of decentralization. A household electricity cost optimization model, together with a northern European electricity system dispatch model form the basis for the analysis of individual prosumer households (**Paper I**). An optimization model to represent electricity trading between prosumers has been developed to allow investigations at the prosumer community level (**Paper II**). Finally, a model has been developed to investigate city-level energy systems (**Paper III**), which includes optimization of the electricity, heat, and transport sectors combined.

**Table 2** provides an overview of the modeling methods utilized in this thesis, as well as their input data and most of the important output parameters. The *ELIN/EPOD modeling* package has been previously developed to study cost-optimal investment and dispatch in the European electricity system [78–81]. For this work, two modules for the EPOD model have been utilized: 1) a module designed by Goop et al. [82], which incorporates cost-optimal investment and dispatch of PV and battery systems by prosumer households in an iterative process into the dispatch modeling; and 2) a module that was developed for this work and that extends the EPOD dispatch model with equations to include the central control of battery storage systems. Using both modules together allows for a comparison of household-controlled and system-controlled battery system operations, as described in **Paper I**.

The optimization models to study *prosumer communities* and the *city energy system* have been developed for **Papers II** and **III**. The *prosumer community* model makes use of Swedish household load data and calculates the prosumer-optimal investment and operation of PV-battery systems both for prosumers who are acting individually and prosumers who are part of a prosumer electricity trading community. The *city energy system optimization* model is designed to investigate local balancing in the electricity and heating sectors (in a forthcoming version of the model, the transport sector is also included) within the urban energy system. The model co-optimizes the investment and operation of electricity generation units, combined heat and power plants, as well as electricity and thermal storage systems, while taking into account the connection capacity between the city energy system and the national electricity grid.

The following sections give an overview of the most important characteristics of the modeling methods utilized, and detailed mathematical formulations are provided in the appended papers.

**Table 2: Summary of modeling approaches, including the input data and main output parameters utilized to study the different levels of decentralization in this thesis.**

	<b>ELIN/EPOD modeling package</b>	<b>Prosumer community model</b>	<b>City energy system optimization model</b>
<b>Paper</b>	I	II	III
<b>System levels included</b>	Individual prosumer households & Nordic electricity system	Individual prosumer households & Prosumers in electricity trading communities	Smart city energy system
<b>Model package/development</b>	EPOD modeling, including household PV-battery investments according to [82,83] plus adaptations to EPOD [80] to include battery storage	Prosumer community model developed for this work	City energy system optimization model developed for this work
<b>Sectors considered</b>	Electricity	Electricity	Electricity, district heating (transport module upcoming)
<b>Input data</b>	Measured load curves from a set of Swedish households, input data to the EPOD model (see [80,83] and the appended <b>Paper I</b> )	Measured load curves from a set of Swedish households, solar generation profiles acquired from [84], hourly electricity price curve from the EPOD model	Load curves for urban electricity and district heating demand, local solar generation profile, electricity price curve from EPOD model
<b>Modeling output</b>	Operation of household PV-battery systems from the prosumer household and the electricity system perspectives, dispatch and operation of the electricity system	Required capacity and operation of PV-battery systems for individual prosumers and prosumer communities	Technology mix in electricity and heating system for a growing and carbon-neutral city energy system, system operation and utilization of flexibilities and synergies

### *3.1. ELIN/EPOD: THE CENTRALIZED ELECTRICITY SYSTEM*

The modeling of the centralized electricity system is utilized in the following two ways:

**1) Prosumer households within the centralized electricity system (Paper I):**

In **Paper I**, the operation of prosumer household PV-battery systems is studied as part of the Nordic centralized electricity system. For this analysis, household PV-battery systems have been directly integrated into the dispatch modeling of the centralized electricity system, and two modules of the EPOD model have been utilized (see Chapter 3.2).

**2) Interactions of prosumer households, prosumer communities, and smart cities with the centralized electricity system (Papers II and III):**

The decentralized systems in this thesis are not studied in isolation. Prosumer households, prosumer communities, and smart cities interact with the centralized electricity system through the patterns of their electricity trading, i.e., the times and amounts of electricity purchased from and fed into the national grid. In **Papers II and III**, an hourly profile for the marginal costs of electricity generation from the EPOD dispatch modeling of Northern Europe is used as an input to the prosumer community model and the city energy optimization model. This electricity price curve gives an indication as to when electricity feed-in or increased electricity consumption from the decentralized structures is most beneficial for or costly to the centralized electricity system.

The ELIN/EPOD modeling package was first presented by Odenberger and Unger [78,79] and thereafter refined by Göransson et al. [80] and Goop et al. [81]. The ELIN (ELectricity INvestment) model optimizes electricity generation and transmission capacity in the European Union, Norway and Switzerland up to Year 2050 in different scenarios (divided into 50 regions, as defined by bottlenecks in the capacities of power lines), taking into account aging of the current power plant portfolio. For this thesis, outputs from the ELIN model regarding the system compositions and power plant capacities have been utilized as an input to the EPOD dispatch model. The EPOD (Electric POWER Dispatch) model minimizes the total cost for electricity generation (for the same 50 regions as in ELIN). Congestion in the power lines between regions results in different marginal costs for electricity generation in different regions, which is utilized as a proxy for the electricity price. During times of high marginal costs for electricity, decentralized electricity generation could be of greater value, provided that the value of the generation is also seen by prosumer households, prosumer communities, and other decentralized systems.

### *3.2. ELIN/EPOD: HOUSEHOLD PROSUMERS WITHIN THE ELECTRICITY SYSTEM*

The literature offers methods and analyses to study self-consumption and self-sufficiency within single prosumer households (Chapter 2.1.1). In this thesis, the focus therefore is on studying prosumer households as part of the electricity system. The methodology applied in **Paper I** highlights how the operation of household-scale PV-battery systems changes when optimized from the prosumer household perspective, as compared to the electricity system perspective, as well as the effect that this has on the electricity system dispatch. For both these perspectives, the outputs related to

electricity generation and transmission capacity from the ELIN model are utilized as an input to the EPOD modeling. For the study described in **Paper I**, the EPOD model is run for 25 regions in Northern Europe (i.e. Nordic countries plus neighboring regions to account for electricity trade to and from the Nordic regions, see **Paper I** for a map of all the regions included), for both the prosumer household and electricity system perspectives.

- *The prosumer household perspective:* The investment in household PV-battery systems is modeled by combining a household electricity cost optimization model with the EPOD model. Prosumer households in the household cost optimization determine the cost-optimal capacities of PV-battery systems based on their electricity demand profile and an hourly electricity price (including taxes and fees charged to household customers). The household electricity cost optimization is iteratively connected to the EPOD modeling tool using a method developed by Goop et al. [82,83]. Through this coupling of the two models, it is possible to consider a change in household net electricity loads in the EPOD dispatch modeling (i.e., the electricity consumed by the households from the centralized system each hour after considering in-house PV generation and battery system charging and discharging within the households). This in turn creates an updated electricity price curve from the EPOD model, which is used for the electricity cost optimization in the prosumer households. As the household electricity cost module is integrated into the EPOD model, the dispatch of the electricity system considering the new net-load curve from prosumer households can also be analyzed. Prosumer households have been considered in the two southernmost market regions in Sweden.
- *The electricity system perspective:* To represent the system-controlled operation of (PV) battery systems, a set of equations has been added to the EPOD model to describe the charging, discharging, and storage levels of prosumer battery systems as part of the total system dispatch. The PV-battery capacity determined to be optimal for prosumer households (see the prosumer household perspective above) has been added as an aggregate capacity in each of the two southernmost regions in the EPOD modeling. An equation to represent the battery storage levels in both of these regions is included in the model, and variables representing the charging and discharging of the battery systems are added to the nodal electricity balance in each region within the dispatch model. Generation from household-scale PV systems is added to the electricity generation from other technologies in the dispatch model.

For the analysis of prosumer households within the electricity system, a dataset of measured Swedish household load profiles created in a project conducted by E.ON in Sweden has been utilized. The data were first presented and prepared by Nyholm et al. [21]. For utilization within the EPOD model, the data have been scaled up to represent residential houses in the two southernmost market regions in Sweden, in different household categories (for details, see [82,85]).

### 3.3. THE PROSUMER COMMUNITY MODEL

The prosumer community optimization model developed for **Paper II** has been designed to directly compare PV-battery system investments and operation at the individual prosumer household level with a prosumer electricity trading community, while in both cases minimizing the annual electricity cost for the total of all modeled households. Thus, the following two cases are compared:

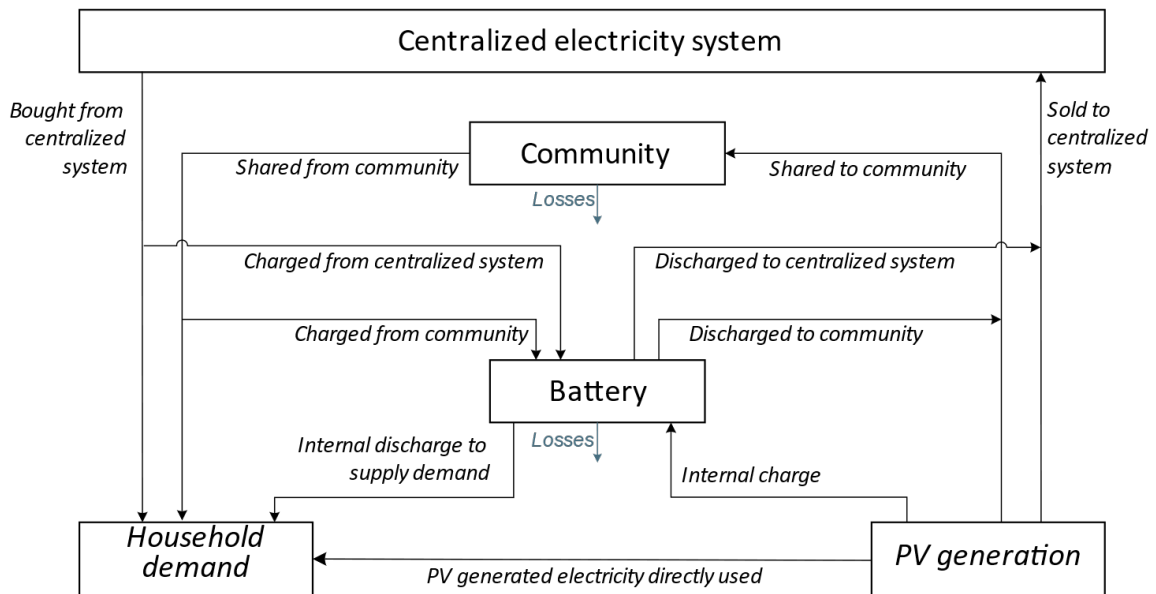
- *Individual prosumers* invest in and operate their PV-battery systems independently and buy and feed back electricity directly from and to the centralized electricity system, respectively.
- In a *prosumer community*, the PV-battery system investments and operation are optimized for the entire prosumer community. Electricity trading is assumed to be possible between the prosumer households within the prosumer community, so as to meet each household's electricity demand or to charge the households' battery systems. Interaction with the centralized system by the prosumer community is possible, i.e., the purchasing of electricity and the feeding back of surplus electricity.

The prosumer community model is a linear cost-optimization model that minimizes the annual electricity cost for the total of all the modeled households according to Eq. (1).

$$C^{tot} = \sum_p (c_p^{el} + c_p^{inv}) \quad (1)$$

The annual household electricity costs ( $C^{tot}$ ) here consist of the variable electricity costs ( $c_p^{el}$ ) in each prosumer household  $p$ , as well as the annualized costs to invest in PV-battery systems ( $c_p^{inv}$ ) at the household-level. The variable electricity costs for prosumer households are composed of the costs to purchase electricity from the centralized system minus the reimbursement that is paid to prosumers for feeding back electricity to the national grid, both of which are based on the hourly electricity price profile. In this model, households pay an energy tax and energy-based grid fees on top of the hourly electricity price for electricity that they buy from the centralized system; for electricity fed to the national grid, no VAT or income tax is paid (as in the current Swedish pricing scheme) and a small reimbursement is applied to the hourly electricity price. The conditions considered for the electricity trading community are the same as those assumed for individual prosumers, and thus, this assumption reflects an extension of the concept of self-consumption in individual households.

**Figure 2** illustrates the electricity flows that are considered in the model. Each household's electricity demand can be supplied by electricity generated by the in-house PV panel, electricity bought from the centralized system or, in the cases where prosumer communities are modeled, by electricity that has been shared by another prosumer household within the trading community. Taking into account the different options for electricity utilization by the prosumer household allows the method to consider two types of usage for the prosumer battery: a) to store PV-generated electricity for the self-consumption in the prosumer household as well as in the prosumer trading community; and b) to react to variations in electricity prices from the centralized system and, consequently, prioritize the purchase of electricity during low-price hours and the feed-back of electricity to the centralized system during higher-price hours.



**Figure 2: Schematic of the electricity flows within the prosumer household (i.e. the boxes *Household demand*, *PV generation* and *Battery*), to and from the centralized system, and to and from the prosumer electricity trading community [adapted from Paper II].**

Two different constraints are imposed on the model to represent and analyze two different dynamics underlying the prosumer electricity trading communities:

- *The objective to reach a certain level of self-sufficiency.* This constraint represents the ambition of prosumer communities to become more energy-independent and less reliant on energy utilities for the supply of electricity.
- *A limit on the electricity connection capacity to and from the centralized system.* This constraint reflects a situation where prosumer households reduce their reliance on the grid operator, i.e., by limiting the capacity of the connection. This constraint also represents a future development in which not only a larger share of distributed generation and storage technologies, but also new electricity loads from, for example, the electrification of transport influence the local grid maintenance and a restriction placed on capacity to customers could become relevant.

Both these aspects are modeled and compared for the above-mentioned cases representing individual prosumer households and prosumers as part of a prosumer community.

### 3.4. THE CITY ENERGY SYSTEM OPTIMIZATION MODEL

To analyze the smart city energy system in **Paper III**, a linear optimization model has been developed that takes into account the integration of and flexibility in the electricity and heating sectors. By combining a broad technology portfolio with an hourly modeling time resolution over a full year, local energy balancing can be analyzed in the short and medium terms. The model includes technologies for electricity generation (solar PV and peak-power gas turbines), heat production (heat-only boilers fired by different fuels, including electric boilers, and industrial excess heat), and CHP plants, as well as storage units for electricity (battery technologies) and heat (tank, pit, and borehole storage systems). The objective is to minimize the total costs of investment and operation for the electricity and heating sectors, which is formulated as follows:

$$\text{MIN } C^{tot} = \sum_{i \in I} (C_i^{inv} s_i + \sum_{t \in T} (C_i^{run} p_{i,t} + C_i^{run} q_{i,t})) + \sum_{t \in T} C_t^{el} w_t \quad (2)$$

$C_i^{inv} s_i$  represents the investment costs for all technologies  $i$ ,  $C_i^{run} p_{i,t}$  and  $C_i^{run} q_{i,t}$  are the running costs for the electricity generation (including CHP) and heat production technologies, respectively, for all time-steps  $i$ . The model allows for the import of electricity to the city according to an hourly electricity price, defined as  $C_t^{el} w_t$ .

**Figure 3** depicts the city energy optimization model and shows how the different sectors are connected in the modeling process. The city electricity load and heating demand, which is an input to the modeling, is influenced by the assumptions to represent future city growth. The electricity demand can be covered in part by electricity imports from the centralized system, although this is limited by the connection capacity into the city. The growth of city areas and electrification can lead to situations in which the connection capacity into the city is not sufficiently large to supply the full electricity load, as also discussed in Chapter 2.3. (The two modules for the electrification of transport indicated in gray type on the left side of the figure will be included in forthcoming studies with the model). Therefore, local technologies for electricity generation can also be utilized in the model to supply the demand. Heat demand has to be fully supplied from within the city boundaries, since the model does not allow the import of heat to the city district heating system. No export of electricity to the centralized system is currently considered in the model, so as to focus the analysis on the supply of electricity and heating demands in the city through local generation and storage technologies. Electricity and heating demands are subject to seasonal, weekly, diurnal and hourly variations. Variations on a time resolution shorter than 1 hour are not part of this work. The technology choice in the modeling makes it possible to investigate the role of the flexibility provided by storage systems for electricity and heat, as well as the linkages between the electricity and heating sectors through technologies such as heat pumps and electric boilers.

Future model developments will include the electricity demands and charging strategies of electrified transport and other city energy system scenarios, for instance, the production of hydrogen. These aspects are discussed in Chapter 6.

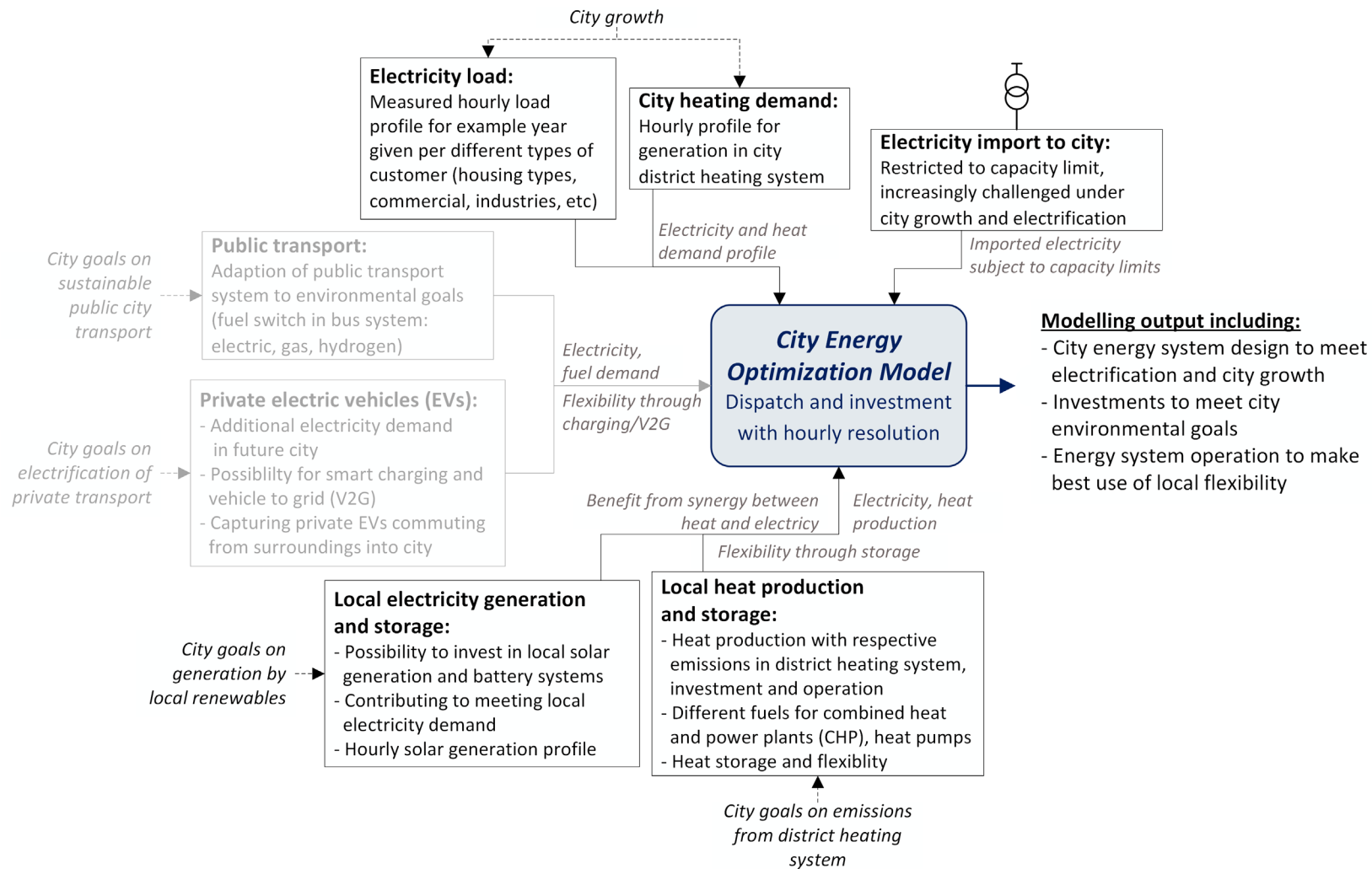


Figure 3: Schematic of the city energy optimization model [Paper III]. Gray boxes are modules that are under development and that will be included in future work.

## 4. MAIN RESULTS AND DISCUSSION

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*In this section, the main findings concerning the techno-economic parameters, the self-consumption, and the interactions with the centralized system are summarized for the three levels of decentralization studied, i.e., individual prosumer households, prosumer electricity trading communities, and smart integrated cities.*

### 4.1. PROSUMER HOUSEHOLDS AND THE ELECTRICITY SYSTEM

The parameters that drive the operation of local generation and storage systems within prosumer households differ from the factors that steer the operation of these technologies from the electricity system perspective. The modeling used in **Paper I** shows a clear diurnal shape for the battery system charge and discharge patterns when operated as optimal for the prosumer households, i.e., minimizing the annual household electricity cost. When modeled as part of the total Nordic electricity system operation, i.e., minimizing costs for electricity generation in the Nordic system over 1 year, battery systems are utilized less frequently, yet they are often charged or discharged completely within 1 hour.

In prosumer households, the operation of PV-battery systems is closely related to the household electricity demand. With a pricing scheme within which electricity that is locally self-consumed within the household is exempt from taxes and fees placed on top of the electricity market prices for purchase from the grid, as modeled in this work and currently the case in Sweden, a clear economic incentive exists for prosumer households to utilize their battery systems to match electricity generation from solar PV to their electricity consumption. **Figure 4** illustrates the relationships between solar generation patterns, the household load, and the battery system operation for the prosumer households. In the first panel of Figure 4, a clear diurnal pattern for solar generation and electricity demand can be seen for two summer weeks from the modeling. The same diurnal shape is found for the storage level in the battery, when operated from the perspective of prosumer households, as shown in red in the third panel of the figure. A high level of in-house self-consumption is achieved by charging the prosumer battery system during daytime (when local solar generation is available) and discharging at the end of the day and during the morning hours to supply the household demand.

When household battery systems are utilized for maximum benefit from the centralized electricity system's perspective (i.e., so as to minimize electricity generation costs in the Nordic system) the batteries hold the same storage level for much longer periods of time and are charged and discharged less frequently, albeit with more energy at each time (see the gray dotted lines in Figure 4). From the prosumer household perspective, there is value in charging batteries with solar power that is generated in the middle of the day. When instead operating the battery systems from the electricity system perspective they are used to avoid hours of high marginal costs for electricity generation by discharging energy from the battery systems during these hours. Such hours of high marginal costs are often related to a low output from wind power generation and a high electricity demand in the system.

For the conditions modeled in this work, the designs and levels of the tariff schemes exert stronger impacts on the PV-battery system operation from the prosumer household perspective than do the electricity price levels. Variations in the electricity price can be expected to be larger in regions with a high share of fluctuating non-dispatchable generation and with few options for variation management. The Nordic electricity system represented in the present work has a substantial capacity of reservoir hydropower stations that can contribute to balancing variations in the electricity price. The average electricity price level depends on the technologies available for electricity generation in the system studied and their respective operational costs. A pricing system that includes a higher level of compensation for electricity fed to the centralized system, through for example a feed-in tariff, could make local self-consumption less attractive to prosumer households. The grid fees considered in this work are based on the energy consumed. With a different tariff structure, prosumer household could also be charged for the peak capacity that they utilize during a certain time period, which also affects the prosumers' interactions with the centralized system.



**Figure 4: Load and PV generation profiles in the prosumer households. Shown are the charge (on the positive y-axis) and discharge (negative y-axis) patterns and storage levels of the batteries from the system perspective and from the prosumer household perspective. The data are for two modeled summer weeks, shown as the aggregate for the southernmost market region in Sweden. [adapted from Paper I].**

The ways in which prosumer systems affect the operation of the centralized electricity system differ between the case in which prosumer households operate PV-battery systems in order to minimize their electricity costs and that in which the PV-battery systems are operated as optimal from the

perspective of the electricity system (equivalent to central control of battery system operation). When the battery system operation is included in the minimization of total electricity system generation costs, i.e., the system perspective, a number of start-ups of thermal power plants and some generation from peak-power plants (which are the most expensive to run) can be avoided. The central control of the battery system from an electricity system perspective has the potential to reduce the average running costs in the two southernmost Swedish regions by 2.3% and 4.0%, respectively. However, even if the system savings could be used to reimburse prosumer households for central control of their battery systems the total system value created by central dispatch of batteries is lower than what the households could gain from operating battery systems in a way that is beneficial to them.

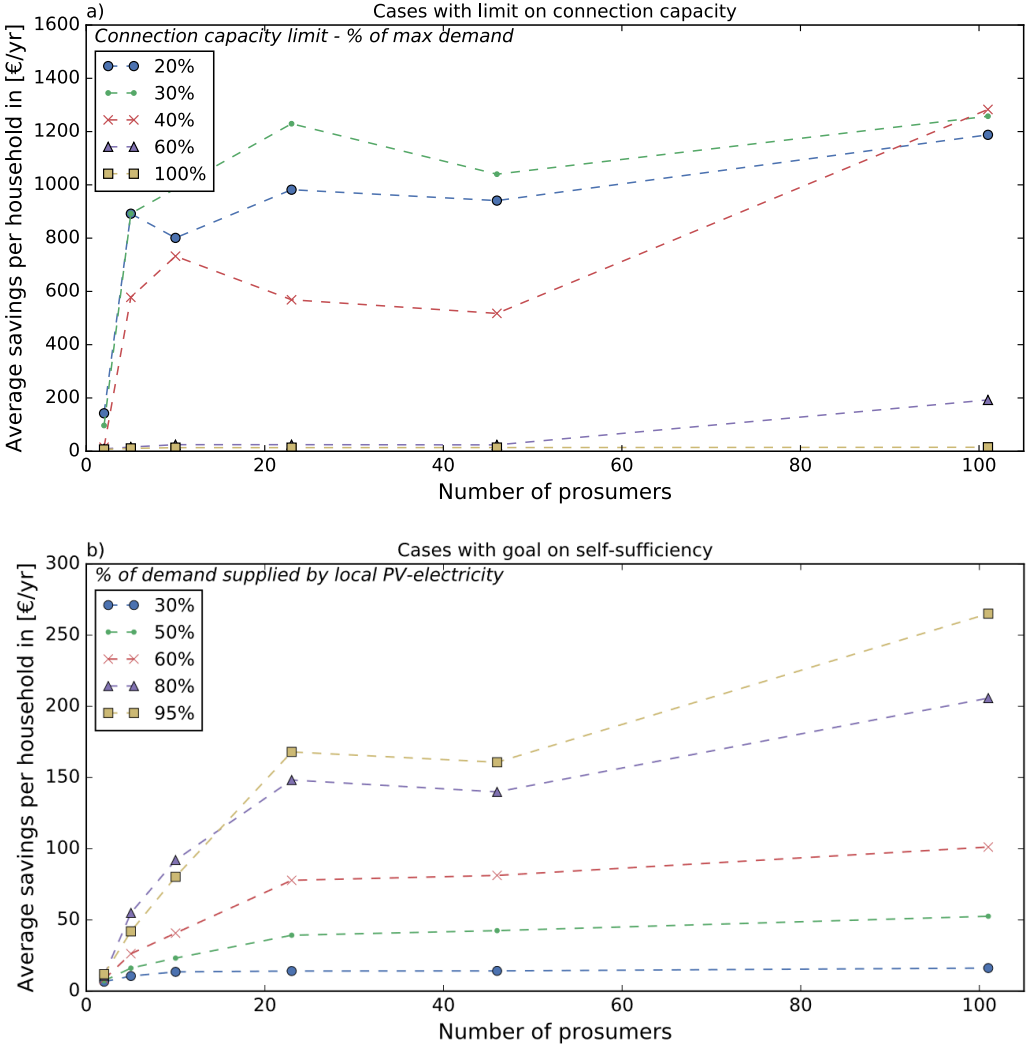
#### *4.2. PROSUMER COMMUNITIES – ENERGY, CAPACITY AND TRADING PATTERN TO THE GRID*

Grouping of prosumer households into electricity trading communities enables local self-consumption and energy balancing on a larger scale than that of the individual household. Thus, sharing locally generated electricity has the potential to increase the value of PV-battery systems for prosumer households. The modeling carried out in **Paper II** reveals the accrual of savings in prosumer electricity costs already when there is collaboration between five prosumer households. A larger benefit for prosumer households is found in model runs that include a limit on connection capacity, as compared to the model runs that include a goal of a certain level self-sufficiency. For the households, the greatest benefit associated with being part of a prosumer community rather than acting individually appears in cases with very strict constraints on the connection capacity limit. **Figure 5** shows the savings per average prosumer household and year, for a range of prosumer group sizes (*x*-axis) and the two different modeling constraints for: a) a limit on transfer capacity; and b) a set goal in relation to the self-sufficiency level.

The savings per average prosumer household are clearly greater in Figure 5a than in Figure 5b (note the different scales on the *y*-axes in Figure 5, a and b). The savings for prosumer households in this work are affected by savings on the variable costs for electricity and partly by the size of the required investments in PV and battery systems. Local self-consumption and energy balancing affect the variable costs of electricity in the prosumer households. When electricity can be shared in a prosumer community there are more possibilities to utilize locally the PV-generated electricity, thereby avoiding some of the taxes and grid fees payable on electricity purchased from the centralized system. However, this requires regulations pertaining to the exchange of electricity between prosumer households; such regulations are not in place today. Being able to utilize the battery capacity of the whole prosumer community also increases the possibilities to react to hourly variations in electricity prices. Smaller investments, i.e., smaller PV-battery system capacities are needed in a prosumer trading community when prosumer households can share the utilization of these units.

Distinctive differences in the capacities required for individual prosumer households as compared to prosumers acting as part of a prosumer trading community, are found in the modeling runs that consider a 40% or stricter limit on connection capacity. At a connection capacity limit of 40%, PV capacities of 10–20 kWp are needed per average prosumer household to meet the constraint. Battery capacities for this connection capacity limit range from around 20-50 kWh per average prosumer

household. Readers are referred to **Paper II** for more details on the investments in PV-battery systems. When analyzing prosumer communities for the purpose of self-sufficiency only minor differences are detected between the PV-battery capacities required for individual prosumers and prosumers within a community. For the example of a self-sufficiency level of 60%, around 20 kWp of PV capacity and 25 kWh of battery capacity are required. With both a limit on connection capacity and a self-sufficiency goal, the PV capacities required increase dramatically with a limit stricter than those in the examples given above.



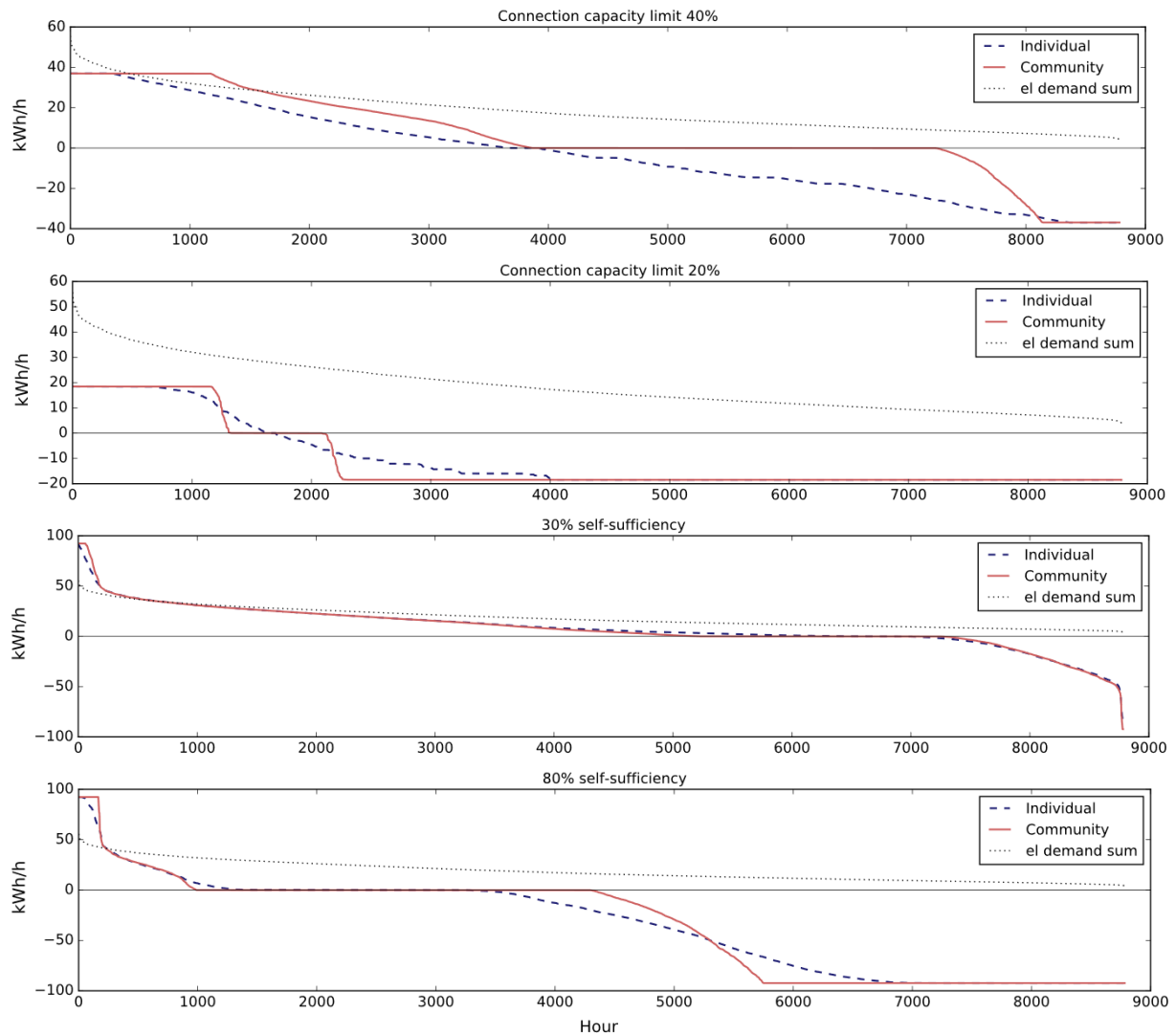
**Figure 5: Savings associated with being part of a prosumer community rather than acting as an individual prosumer, as given for the average household, for the purpose of: a) reducing the connection capacity to the centralized system; and b) increasing self-sufficiency. The modeling is carried out for different limits on the two constraints imposed on connection capacity and self-sufficiency (different lines in the figure) and for different numbers of prosumers, i.e., 2, 5, 10, 23, 46 and 101 prosumer households (on the x-axis). Note the different scales on the y-axes. [Paper II].**

Thus, prosumer electricity trading communities are more beneficial in terms of reducing the connection capacity than in reaching a certain level of self-sufficiency. This is mainly due to the nature of residential electricity demand profiles. Residential household electricity demand patterns differ with regards to the timing of their peak demand, which to a large extent depends on occupant behavior

and coincides with the utilization of, for example, appliances. However, a large share of the electricity demand (e.g., from electric heating, refrigeration and ventilation) is similar in the different prosumer households. To achieve high levels of self-sufficiency, a large share of the household electricity demand has to be covered by locally generated electricity. For the purpose of self-sufficiency, therefore, prosumer electricity trading communities can only provide a small benefit compared to individual prosumers.

The interactions of prosumer households and prosumer electricity trading communities with the centralized electricity system can be described in terms of the amounts of electricity that they purchase and the capacities that they utilize for the purchase and feed-back of electricity. In **Figure 6**, the trading pattern (i.e., the electricity purchased from and fed back) to the centralized electricity system is plotted. The amount of electricity purchased is shown on the positive  $y$ -axis, while the amount of electricity fed back to the centralized electricity system is shown on the negative  $y$ -axis. The values in the graph are sorted from the hour with the highest amount of purchased electricity (to the left) to the hour with the highest feed-back to the electricity system (to the right). The biggest difference in the shape of the curve for individual prosumers (black dotted line) and those that are part of a prosumer community (red line) is the number of hours with no electricity exchange to the centralized system. The plateau on the zero-line illustrates full local energy balancing. When prosumer households can share electricity amongst each other fewer hours of interaction with the centralized system (purchase as well as feed-back of electricity) are needed. The difference in trading patterns to the centralized system between individual prosumers and the electricity trading communities indicates that it is important to consider local energy balancing is important when discussing the impact from a high number of prosumers.

The modeling of prosumer electricity trading communities in this work is limited to the implementation of PV-battery systems, technologies which are likely to be the first to become prominent at the household level. Taking into account the charging (and possibly discharging) of electric vehicles inside prosumer households and prosumer communities can be assumed to have impacts on self-consumption and savings within prosumer communities. Electric vehicles offer another option to self-consume locally the electricity generated by PV panels. They could thereby replace some of the capacity in stationary batteries within prosumer households and could influence the dynamics of local self-consumption in prosumer communities. Moreover, the representation of flexible household demand through demand-side management, especially the control of electric heating equipment, could affect the benefit that prosumer households derive from being part of a prosumer community. Including different types of electricity consumers, such as supermarkets and office buildings, would introduce differently shaped load profiles and would influence both the dynamics within a local energy community and the benefit that could be gained from being part of such a community.



**Figure 6: Trading patterns of individual prosumers and prosumers as part of an electricity trading community, for a limit of 40% or 20% (of the maximum load) imposed on the connection capacity and for goals of 30% and 80% self-sufficiency. The data shown are from model runs that include ten prosumer households; the line for individual prosumers represents the aggregated trading pattern of all ten households (i.e., the profile of all households is summed to an aggregate curve and then sorted).**

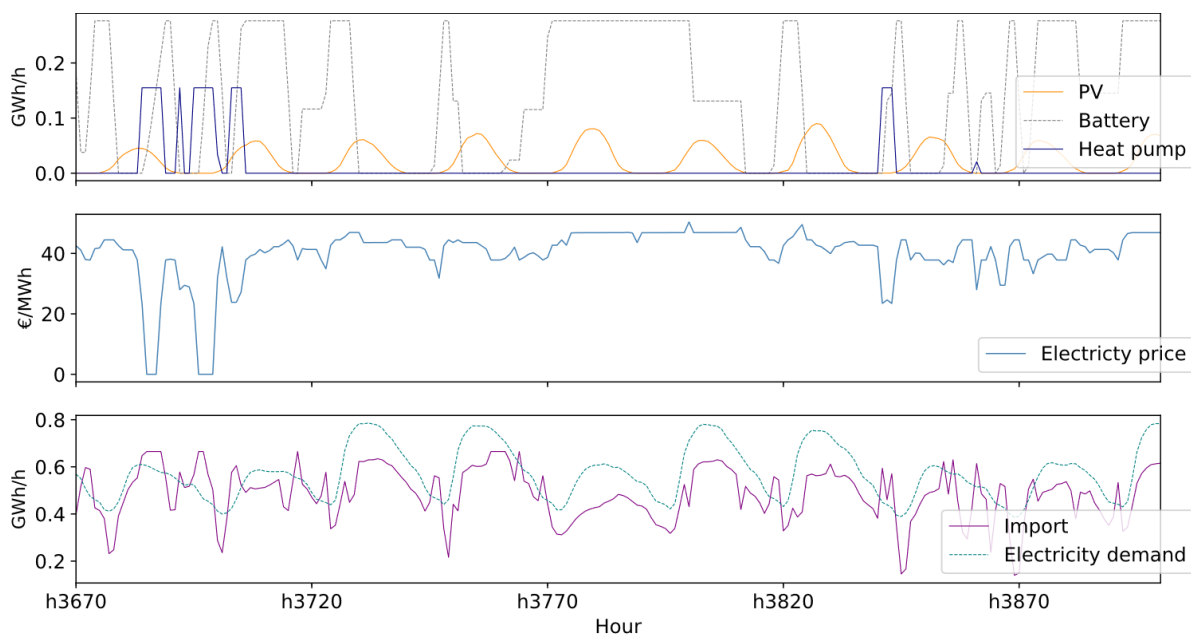
#### 4.3. LOCAL BALANCING OF ELECTRICITY AND HEAT IN FUTURE SMART CITIES

A first version of the city energy system optimization model has been applied to the city of Gothenburg. In the case study of Gothenburg, a future with low-carbon electricity and district heating systems is modeled under the assumption of growth in the electricity and heating demands (for details on the set-up of the case study, see **Paper III**). Growth in demand with a limited connection capacity from the centralized system into the city leads to the adoption of local generation and storage technologies.

In **Paper III**, clear synergies between the electricity and heating systems are identified. The results also highlight the importance of local storage systems within the low-carbon urban energy system. The interactions between the urban electricity system and the district heating system and the choice of storage technologies depend on technology and fuel cost assumptions (PV, battery, and biomass fuel

prices are varied in the modeling). Heating technologies that run on electricity (power-to-heat technologies), such as electric boilers and heat pumps, are especially prominent in the model cases with low PV costs. With the availability of low-cost, locally PV-generated electricity, the power-to-heat technologies are utilized together with thermal storages. Different storage technologies are used, ranging from those suitable for short-term storage (several hours up to days) to those that can serve as seasonal thermal storage and thereby facilitate local energy balancing. For details on the technology portfolio and the annual operation in different model runs, the reader is referred to **Paper III**. The focus in this section is on the relationship between the operation of different local energy technologies and the impact of local energy technologies on the interaction with the centralized system.

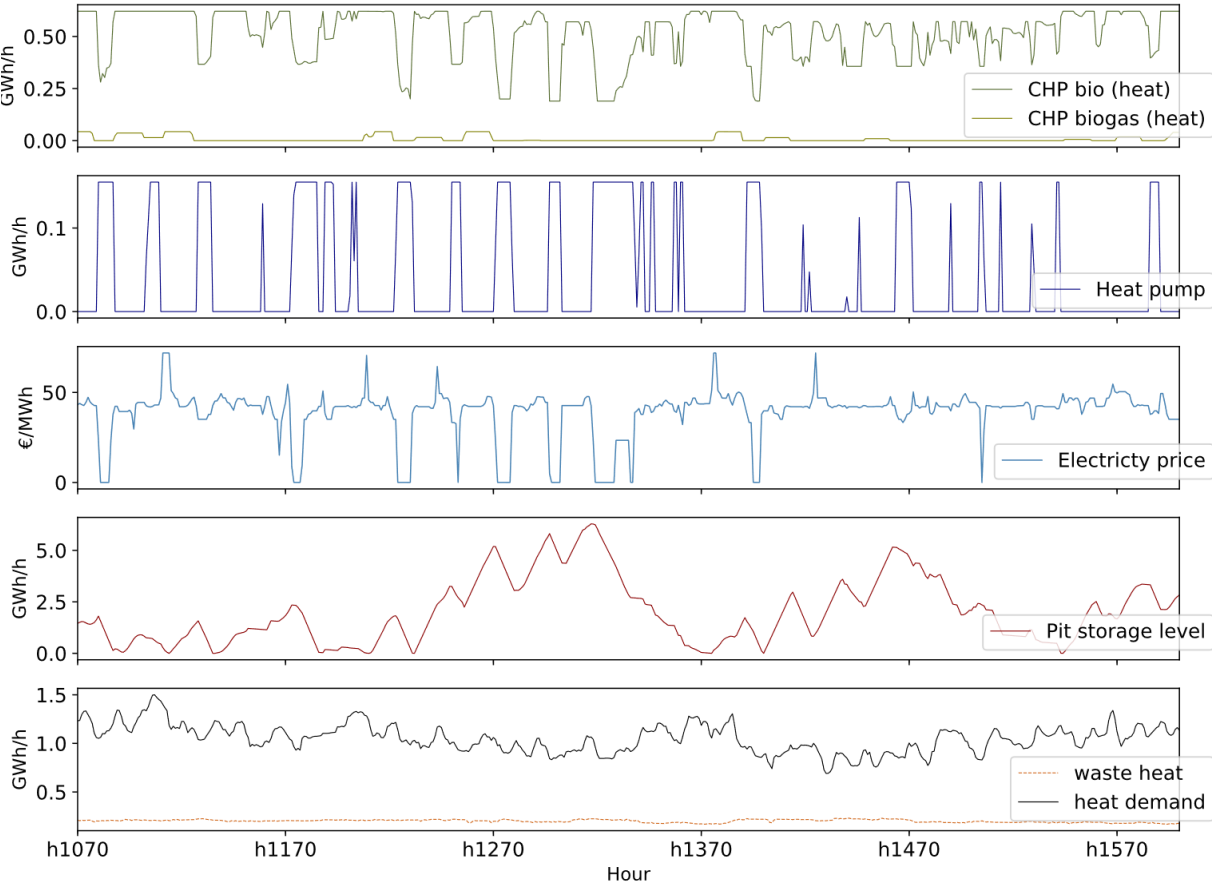
**Figure 7** shows the relationship between the operation of PV, battery, and heat pump technologies, the price for imported electricity, and the electricity demand and electricity imports of the city over ten summer days, for the case study of Gothenburg. The results are plotted for a case with low prices for biomass (i.e., the ‘Low Cost Bio’ case, **Paper III**), which includes more biomass-fueled capacity in the system than in the modeled case with low costs for solar PV and higher costs for biomass (i.e., the ‘Low Cost PV’ case, **Paper III**). In the figure it can be seen that PV generation coincides with hours of high electricity demand in the city. Electricity import to the city is not fully utilized when local electricity generation from solar PV and CHP units (not included in the figure) is available. In addition, heat pumps and battery storage technologies influence the pattern of electricity imports from the centralized system. Heat pumps are operated during hours of low prices for imported electricity. Batteries are used to shift electricity import between hours with lower electricity prices and hours with higher electricity prices. Battery systems are, therefore, not only charged during hours of very low electricity prices, when heat pumps are also run, but also store electricity in between different hours with electricity price variations.



**Figure 7: Operational patterns of PV, batteries, and heat pumps, with the hourly price of imported electricity and the hourly profile for electricity import to and electricity demand within the city. Data shown are for ten summer days in the modeling for the city of Gothenburg, for a case with low biomass costs.**

In a case with lower solar PV investment costs (not shown in Figure 7), more electricity generation from PV is available in the city energy system. This entails a larger share of the local electricity generation, which means that heat pumps and battery systems are not only operated based on the price of imported electricity, but also to exploit the PV-generated electricity, which otherwise would have to be curtailed, within in the city. The case with large PV capacities in place corresponds to larger variations in the electricity import pattern to the city during the summer season (many hours of zero import during the day and large imports during night hours) and many hours of import at full capacity during the winter season.

In **Figure 8**, the relationship between heat production from CHP plants and heat pumps and the utilization of the thermal pit storage is shown. The heat demand in the city energy system varies over the different days and weeks, and is clearly higher during the winter than during the summer. Parts of the demand can be covered by industrial excess or waste heat that is available in the city. Heat pumps are utilized during hours of very low electricity prices, as shown in Figure 7. Most of the hours of heat pump operation are connected to reduced output from the CHP units. The CHP units operate at different levels of output, as shown in Figure 8, and are subject to costs and constraints on cycling. Therefore, the pit storage is also charged and discharged during the periods when the CHP units and heat pumps change their outputs, in order to cover smaller variations in heat demand. The storage level in the pit storage is highest just before the peak heat demand in winter time.



**Figure 8: Heat production from combined heat and power (CHP) units and heat pumps, the price of imported electricity, the storage level in the pit storage system, the waste heat utilized in the city, and the hourly profile for heat demand within the city. Data shown are for three winter weeks in the modeling of the case study of the city of Gothenburg.**

The results from the modeling in **Paper III** show clear relationships between the operation of heat pumps and battery storage systems and the price of electricity imports to the city. The hourly variations in the price of imported electricity provide the possibility to adapt local energy balancing so as to supply the city with energy at the lowest costs. Modeling the city energy system optimization with a flat electricity price curve instead of an hourly varying electricity price profile for imported electricity can be assumed to affect the results for the capacities and operation of power-to-heat and battery storage technologies. With no variation in the prices to import electricity to the city, the possibility to make use of locally generated electricity would dominate the investment in and operation of these technologies. Considering the possibility for exporting electricity from the city energy system (not the case in the current version of the city optimization model, see Chapter 3.4) could also influence the operation of battery storage systems. In that case, the discharge of battery systems would not only be incentivized during hours of high electricity prices, in order to avoid expensive imports to the city, but also in order to export electricity to the centralized system. Introducing the possibility to export electricity into the city energy system modeling can also be expected to reduce investments in battery systems in the city, as electricity can be exported instead of being stored.

The modeling in **Paper III** focuses on local measures for the generation and balancing of electricity and heat in the city energy system. Another option to meet electrification and city growth involves expanding the connection capacity (e.g., through the construction of new cables). Different stakeholders are involved in each of these alternatives, which is likely to create different conditions for their implementation.



## 5. CONCLUSIONS

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*This thesis provide insights into the value and utilization of energy technologies at different levels of decentralization within the energy system. The methods developed and applied in the present work are used to investigate prosumers of electricity from the individual and community perspectives (**Papers I and II**), the perspective of planning and operation of the Nordic electricity system (**Paper I**), as well as the perspective of urban energy system planning (**Paper III**, for a case study of Gothenburg).*

Related to the three research questions posed in this thesis, the following conclusions can be drawn from the modeling in **Papers I–III**:

**i) Different techno-economic parameters affect the investment and operation of distributed generation and storage technologies at different levels of decentralization.**

At the household level, the operation of battery systems is to a large extent determined by the profiles of the household electricity demand and solar electricity generation, as well as the tariffs and pricing schemes that are in place. Given a tariff system in which taxes are avoided on electricity that is self-consumed behind the meter, it is beneficial for the prosumer households to operate their battery systems for the self-consumption of electricity. With the current levels of taxes and fees in Sweden, the value of self-consumption is higher than the value of reacting to price signals from the centralized system.

The prosumer electricity trading communities in the present work expand the concept of local self-consumption, which means locally generated electricity can be shared amongst prosumer households. The benefit for prosumers with PV-battery systems in joining such a community is mainly linked to the correlation of demand variations between households. Households consume their bulk volumes of electricity at the same time of the day, although residential electricity demand profiles differ with respect to the timing of their absolute peak. Thus, a reduction in connection capacity to the centralized system is achieved at lower cost and lower PV-battery capacities when participating in prosumer communities. It is important to note that prosumers within the community can only derive this benefit when they are connected to each other via the local grid.

At the level of city energy systems, increased electricity demand can be expected in the coming decades owing to increased electrification and city growth. Thus, in the absence of any expansion of the connection capacity to the centralized system, the values of local generation and storage technologies for electricity and heat are increased. At the city level, a larger technology portfolio can be exploited for local energy balancing, as compared to the prosumer household or the prosumer community level. The operation of CHP plants within the city energy system is important for supplying both heat and electricity. With assumptions on low costs for solar PV, more of the heat in the system is supplied by power-to-heat technologies in combination with thermal storage systems. Storage systems are used in the city energy system to shift electricity and heat consumption over time. Power-to-heat technologies, such as heat pumps, are operated so as to utilize electricity when the price for

electricity import to the city is low and during hours of high electricity generation from PV within the city energy system. A higher share of solar PV in the city energy system increases the competitiveness of storage systems and power-to-heat technologies.

**ii) Self-consumption and local energy balancing can be achieved at the prosumer household level, between several prosumers within a prosumer electricity trading community, and when including different energy carriers and sectors in the city energy system.**

In prosumer households, battery systems are operated so as to match the generation from solar PV and the household electricity demand, thereby increasing self-consumption and self-sufficiency. This is the case when pricing schemes are in place such that self-consumed electricity is taxed differently than electricity purchased from the grid. Being part of a prosumer community provides only a small benefit for prosumer households in terms of attaining a certain level of self-sufficiency. Thus, community prosumers need almost the same amount of PV and battery capacity to attain different degrees of self-sufficiency as individual prosumer households. (The analysis has not considered the benefit of community electricity trading to households that do not themselves have a PV-battery system installed.) At the city level, there are clear synergies between the electricity and heating sectors. Storage technologies, together with power-to-heat technologies, are found to interact towards local energy balancing, especially when large solar PV capacities are present in the city energy system. Electricity storage units are typically used for short-term storage, being charged and discharged usually within a day. Thermal storage units tend to be used for longer-term storage; in the modeling, they are combined with the use of power-to-heat technologies, such as heat pumps.

**iii) The interactions with the centralized system and the utilization of connection capacity are affected when generation and storage technologies for electricity and heat are employed in decentralized systems.**

Prosumer households that utilize PV-battery systems for the self-consumption of electricity show a different pattern of interactions with the centralized electricity system than prior to installing in-house generation and storage. Due to local generation, less electricity is purchased from the grid in prosumer households than in households without the possibility to generate electricity locally. In addition, the availability of storage technologies decouples the pattern of purchase from the grid from the pattern of electricity utilization in prosumer household. The trading pattern to the centralized system seen in prosumer communities differs from the trading pattern observed in individual prosumer households. Fewer hours of interaction with the centralized system are found in the case of prosumer communities, when electricity can be shared among prosumer households within the community.

City energy systems, which typically have a low share of local generation technologies, import a large amount of electricity from the centralized system. When cities grow and new electric loads emerge faster than/without any expansion of the connection capacity such import is likely to experience severe stress (in fact, this is already the case in several Swedish cities where there are capacity limitations related to electricity imports to the cities). Installing technologies for the generation and storage of electricity and heat in the city will alter the pattern of electricity import to the city. Battery systems help to adapt the import pattern to the city to the price for importing electricity, especially during the summer season, i.e., larger imports during hours of low prices for imported electricity and lower import during hours of high prices. During the winter season, electricity demand is higher and electricity is more often imported utilizing the maximum connection capacity. Reduced electricity demand partly corresponds to reduced import of electricity.

## 6. OUTLOOK AND FUTURE WORK

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The work on decentralization at different levels can be extended to answer additional research questions. One interesting area for future research is the further development of the city energy optimization model presented in this work with a focus on the following aspects:

- The transportation sector in the optimization of the city energy system. The model used in **Paper III** is so far limited to capturing sectoral integration within the city energy system between the electricity and heating sectors. A switch to low-carbon technologies in the urban transport sector, including vehicles for private and public transport, is essential for the city energy transition. At least a part of the transport system that is currently run on fossil fuels can be expected to be operated using electricity in a near-term future. The impacts associated with the charging and discharging back to the city energy system (i.e., vehicle-to-grid, V2G) of electrified transport on the city energy system is twofold: a) that there will be an increase in electricity demand within the city, which will have to be met; and b) that batteries in electric vehicles will have the possibility to offer flexibility when the timing of charging and V2G is adapted to the electricity consumption and generation within the rest of the city energy system. Another aspect of electrified transport in city energy systems is commuting traffic, which on a regular basis travels from the surrounding areas into the city and vice versa. Smart control of the location and timing for charging these vehicles has the potential to benefit the city energy system. These aspects can be captured by including the driving demand for private and public vehicles in the city energy system optimization, and by accounting for charging and V2G in the electricity balance in the modeling.
- Alternative scenarios for the future city energy system. The modeling can be expanded to include other energy carriers, such as hydrogen. Another option is a more detailed representation of electricity and heating loads in the modeling. Energy efficiency measures and demand-side management both can change the shape and magnitude of energy demand profiles as compared to those that exist today.
- Dividing the city into nodes, corresponding to electricity transfer bottlenecks or types of electricity usage. For this thesis and in **Paper III**, the city energy system has been modeled as a single entity. Different nodes in the city, representing areas such as the inner city or office areas, could be considered. This would enable a more detailed analysis of the types of technology that are needed, as well as in which area they are most beneficial to be connected. Furthermore, this expansion of the modeling allows for an analysis of the bottlenecks for electricity transfer within the city.

In this work, the interactions of prosumer electricity trading communities and smart integrated cities with the centralized system have been modeled based on an electricity price with hourly variations. This electricity price reflects the marginal costs for electricity generation in the centralized system. However, local energy balancing in prosumer communities and smart cities alters the interactions between these decentralized systems and the centralized system. In a future with multiple decentralized systems, this could affect the electricity supply and demand balance in the electricity system, as studied in the context of prosumer households in **Paper I**. Capturing the effect of local energy balancing in smart cities on the centralized system is an interesting topic for further research.

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