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FROM PASSIVE TO ACTIVE ELECTRIC DISTRIBUTION NETWORKS

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Akademisk avhandling

som för avläggande av teknologie doktorsexamen i energi- och miljöteknik vid Akademin för ekonomi, samhälle och teknik kommer att offentligen försvaras fredagen den 17 juni 2016, 09.15 i Paros, Mälardalens högskola, Västerås.

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MÄLARDALEN UNIVERSITY
SWEDEN

Akademin för ekonomi, samhälle och teknik

Abstract

Large penetration of distributed generation from variable renewable energy sources, increased consumption flexibility on the demand side and the electrification of transportation pose great challenges to existing and future electric distribution networks. This thesis studies the roles of several actors involved in electric distribution systems through electricity consumption data analysis and simulation models. Results show that real-time electricity pricing adoption in the residential sector offers economic benefits for end consumers. This occurs even without the adoption of demand-side management strategies, while real-time pricing also brings new opportunities for increasing consumption flexibility. This flexibility will play a critical role in the electrification of transportation, where scheduled charging will be required to allow large penetration of EVs without compromising the network's reliability and to minimize upgrades on the existing grid. All these issues add significant complexity to the existing infrastructure and conventional passive components are no longer sufficient to guarantee safe and reliable network operation. Active distribution networks are therefore required, and consequently robust and flexible modelling and simulation computational tools are needed for their optimal design and control. The modelling approach presented in this thesis offers a viable solution by using an equation-based object-oriented language that allows developing open source network component models that can be shared and used unambiguously across different simulation environments.

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To my wife and all my family

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Last but not least, I would like to thank my beloved wife, Lisette, for being my partner in crime, who spent sleepless nights while I was writing and always motivated me to strive towards my goal.

Summary

Existing and future electric distribution networks face great technical challenges from several directions: on one hand, increased penetration of distributed generation (DG) changes the top-down unidirectional power flow; on the other, electricity markets are becoming more flexible to respond to price fluctuations introduced by larger penetration of variable renewable energy sources, which in turn offers new possibilities for customers to play an active role by adjusting their consumption patterns to market variations; finally, the electrification of transportation will increase the electricity demand rapidly, and therefore an active infrastructure that can supply reliable power at all times must be available.

This thesis studies the roles of two major actors involved in the development of these new active distribution networks: active customers and DG. Making use of data obtained from the mature automated meter reading infrastructure available in Sweden, this work started with an analysis of electricity consumption patterns in a large residential area located in Sollentuna, near Stockholm, with two distinct groups of customers; one group connected to the district heating network and another group with its own heat pump based heating system. This information allowed electricity consumption patterns of both customer groups to be evaluated. Furthermore, in order to determine strategies that would increase consumers' demand flexibility, the Swedish electricity market was studied to identify opportunities from existing electricity contract options that offered variable pricing schemes. Different pricing schemes were evaluated, with special focus on real-time pricing (RTP), to determine the economic impact on customers from both groups. It was found that RTP offered economic benefits on both groups, especially on those that used heat pumps, even without adopting demand-side management strategies.

Additionally, a library was built using the open source, object-oriented modelling language Modelica, to carry out steady-state simulations of low-voltage distribution networks with large penetration of DG. Fur-

thermore, this library was used to simulate different penetration levels of electric vehicles (EVs) to evaluate the impact of different scenarios on electricity consumption and network performance. It was found that with uncontrolled charging, voltage violations occurred with EV penetration levels as low as 30%. Therefore, optimal load shifting strategies should be developed in order to prevent overloading the distribution network during peak hours. Furthermore, the approach used opens new possibilities for unambiguous modelling and simulation of active distribution networks by allowing reuse of model components and sharing of libraries across different simulation platforms.

Sammanfattning

Dagens elnät står inför stora utmaningar: ökad andel distribuerad produktion gör att dagens enkelriktade kraftflöden allt oftare kommer vara dubbelriktat; elmarknaden behöver bli mer flexibel för att svara på förväntade ökade prisfluktuationer på grund av ökad lokal förnybar elproduktion, vilket i sin tur ger nya möjligheter för kunden att spela en mera aktiv roll genom att anpassa sitt konsumtionsmönster till marknadens ökade prisvariationer; slutligen kommer den förväntade elektrifiering av fordon att öka efterfrå gan på el och behovet av en aktiv infrastruktur som kan leverera vid alla tillfällen.

Denna avhandling studerar de två främsta aktörerna som är engagerade i utvecklingen av allt mera aktiva distributionsnät: aktiva kunder och distribuerad elproduktion. Detta arbete började med att analysera elförbrukningsmönster i ett stort bostadsområ de som ligger i Sollentuna utanför Stockholm, med en blandad grupp av konsumenter. Konsumenterna klassificerades i en grupp som är anslutna till fjärrvärmenätet och en andra grupp som har egen värmepump. Elförbrukningsmönstret utvärderades på skilt för dessa bå da kundgrupperna. I syfte att fastställa strategier som kan öka konsumenternas förbrukningsflexibilitet, har kontrakt tillgängliga på den svenska elmarknaden undersökts. De elkontraktens olika prissättningssystemen utvärderades, med fokus på realtidsprissättning, för att fastställa de ekonomiska konsekvenserna för konsumenterna frå n de bå da undersökta grupperna. Det konstaterades att realtidsprissättning erbjuder ekonomiska fördelar för bå da grupperna, särskilt för de konsumtenter som använder värmepumpar.

För att analysera den roll som distribuerad elproduktion har i aktiva distributionsnät, har ett modell-bibliotek utvecklats med hjälp av det objektorienterade och öppna källkodsprå ket Modelica. Modellerna används för att utföra jämvikts (steady-state) simuleringar av lågspänningsdistributionsnät med stor andel av distribuerad elproduktion. Därtill har modellerna använts för att simulera olika penetrationsnivå er av elfordon, för att utvärdera effekterna av olika scenarier på elförbrukning och distributionsnätets stabilitets. Resultatet visar på att med okontrollerad laddning av elfordon inträffar spänningsstörningar redan vid penetrationsnivå er så lå ga som 30 %. Strategier för att flytta en del laster behöver utvecklas för att förhindra överbelastning av distributionsnätet under topplastperioder. Därtill öppnar den använda metoden för nya möjligheter för modellering och simulering av aktiva distributionsnät, genom å teranvändning av modell-komponenter och delning av modell-bibliotek mellan olika simuleringsplattformar.

List of Papers

Publications Included in the Thesis

I J. Campillo, E. Dahlquist, F. Wallin, I. Vassileva. (2016). Real-Time Electricity Pricing in Sweden: is it economically viable for users without demand-side management? Energy Journal DOI:10.1016/j.energy.2016.04.105

II J. Campillo, I. Vassileva, E. Dahlquist, and L. Lundstrm. (2016). Beyond the Building Understanding Building Renovations in Relation to Urban Energy Systems. Journal of Settlements and Spatial Planning, vol. 2016, pp. 3139, DOI:10.19188/04JSSPSI052016

III J. Campillo, F. Wallin, I. Vassileva, and E. Dahlquist.(2012). Electricity demand impact from increased use of ground sourced heat pumps. in 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), 2012, pp. 17. DOI:10.1109/ISGTEurope.2012.6465876

IV I. Vassileva, J. Campillo. (2016). Adoption barriers for Electric Vehicles: Experiences from early Adopters in Sweden. Energy Journal. (*Submitted Feb 2016)

V J. Campillo, S. Barberis, A. Traverso, K. Kyprianidis, I. Vassileva (2015). Open-Source Modelling and Simulation of Microgrids and Active Distribution Networks. In Sustainable Places 2015 (pp. 9199). Sigma Orionis.

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Publications not included in the Thesis

I Vassileva, I., & Campillo, J. (2016). Consumers Perspective on Full-Scale Adoption of Smart Meters: A Case Study in Västerås, Sweden. Resources, 5(1), 3. DOI:10.3390/resources5010003

II J. Campillo, E. Dahlquist, E. Lindhult and I. Vassileva. (2016). Technology Capacity Assessment for Developing City Action Plans to Increase Energy Efficiency in Mid Sized Cities in Europe. Energy Procedia, 2016.

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IV M. Kullman, J. Campillo, E. Dahlquist, C. Fertner, J. Grosse, N. B. Groth, G. Haindlmaier, F. Strohmayer, J. Haselberger (2016). Note : The PLEEC Project Planning for Energy Efficient Cities, Journal of Settlements and Spatial Planning, vol. 2016, no. 8992, p. 3, 2016. DOI:10.19188/09JSSPSI052016

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VII I. Vassileva and J. Campillo. (2014). Increasing energy efficiency in low-income households through targeting awareness and behavioral change. Renewable Energy, 67, 5963. DOI:10.1016/j.renene.2013.11.046

VIII I. Vassileva and J. Campillo. (2014). Eskilstuna (Sweden) as an example of a smart city from an energy efficiency perspective. World Renewable Energy Congress. University of Kingston, London 3-8 August, 2014.

IX J. Campillo, E. Dahlquist and I. Vassileva. (2014). Smart Grid Flexible Modeling and Simulation using Modelica. World Renew-

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X J. Campillo, E. Dahlquist and R. Späth. (2014). Smart Homes as Integrated Living Environments. Volume 4 Intelligent Energy Systems. Handbook of Clean Energy Systems. John Wiley and Sons. DOI:10.1002/9781118991978

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XII I. Vassileva, J. Campillo, F. Wallin and E. Dahlquist. (2013) Comparing the characteristics of Different High-Income Households in Order to Improve Energy Awareness Strategies. 5th International Conference on Applied Energy Pretoria, South Africa, 1-4 July, 2013

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XIV I. Vassileva, J. Campillo, E. Dahlquist. (2013). Increasing energy efficiency in low- income Swedish households through targeting awareness and behavior. World Renewable Energy Congress 2013, Murdoch University, Western Australia, 14-18 July, 2013.

XV J. Campillo, D. Torstensson, F. Wallin, I. Vassileva. (2012). Energy Demand Model Design for Forecasting Electricity Consumption and Simulating Demand Response Scenarios in Sweden. July 5-8, 2012, Suzhou, China.

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Abbreviations

AMR	Automated Meter Reading
AVR	Automated Voltage Regulation
BACS	Building Automation and Control Systems
CHP	Combined Heat and Power
CVR	Conservative Voltage Regulation
DSM	Demand-side Management
DER	Distributed Energy Resources
DG	Distributed Generation
DSO	Distribution System Operator
EV	Electric Vehicle
ECM	Energy Conservation Measures
EMS	Energy Management Systems
GHG	Green House Gas
GSHP	Ground Sourced Heat Pumps
HV	High Voltage
IEA	International Energy Agency
kWe	Kilowatt Electric
kWp	Kilowatt Peak
LV	Low Voltage
MV	Medium Voltage
uGT	Micro Gas Turbine
OECD	Organization for Economic Co-operation and Development
PHEV	Plug-in Hybrid Electric Vehicles
PF	Power Factor
RTP	Real-Time Pricing
PV	Solar Photovoltaic
TOU	Time of Use
TSO	Transmission System Operator
vRES	Variable Renewable Energy Sources
V2G	Vehicle to Grid

Chapter 1

Introduction

1.1 Background and motivation

Electric power has been described by the National Academy of Engineering as the greatest engineering achievement of the 20th century, because the use of electricity has changed our societies to the extent that living without it is almost unthinkable [1]. We need electricity to operate most of our buildings' subsystems, route our traffic, provide security at night, run our factories, preserve our food and filter our water, among other basic needs. Furthermore, in the last decade, our communications needs and the explosion of Internet-connected mobile devices have increased the electricity usage in this sector significantly. If all the server centres required to run existing cloud services were put together, their consumption would rank sixth among all countries [2].

This intertwined relationship creates a direct connection between electricity demand and economic growth. From 1990 to 2013, both global electricity demand and global gross domestic product (GDP) doubled, and so too did coal and gas demand in the power sector, and with that, the related carbon dioxide (CO_2) emissions. In 2013 alone, the power sector accounted for over 60% of the coal and 40% of gas global demand, producing 42% of global energy-related CO_2 emissions. Consequently, the power sector plays a critical role, not just in economic growth, but also in global climate change and local air pollution [3].

Furthermore, according to the International Energy Agency, electricity demand and its associated CO_2 emissions are expected to increase by more than 70% by 2040 compared to 2013 levels [3]. In order to mitigate this impact, renewable energy has received strong support in a growing number of countries, for instance as governmental incentives, tax reductions, feed-in tariffs (FiTs) and changes in the electricity markets, among others.

As a result, renewable power is expected to be the largest contributor of net additions to power capacity over the medium term. As a matter of fact, it experienced its largest growth to date, 130 GW in 2014, and accounted for more than 45% of the net additions to the world's power capacity [4]. While this trend can help mitigate the environmental impact of electricity generation, it does not come without challenges for the system; large penetration of utility-scale variable renewable energy sources (vRES) introduces larger fluctuations on the supply side, and therefore existing prime movers have to ramp up and down their production capacity, often operating in derated mode at lower efficiencies. This operation can lead to increased operation costs and in general, adds more complexity to the operation and control of the power system [5, 6, 7].

On the consumer side, the reduced cost of solar photovoltaic (PV) combined with local incentives for end users (e.g. FiT) has facilitated the penetration of solar PV in residential and commercial areas, connected to low-voltage distribution networks. In 2014, the global PV installed capacity was 176.2 GWp, and it is expected to reach 429 GWp by 2020 [8]. Slightly over 40% of this corresponds to utility-scale PV while nearly 60% corresponds to residential and commercial installations [4].

While the trend is to increase the share of utility-scale PVs in developing markets, such as Western China, India, the Middle East, Africa and countries in the Americas that are not member of the Organization for Economic Co-operation and Development (OECD), in Europe, development is more likely to focus on residential and commercial installations. For instance, in Germany, the share of utility-scale PV is only about 15%, while the remaining 85% corresponds to residential and commercial rooftop mounted installations connected to Low Voltage (LV) and Medium Voltage (MV) distribution networks [9].

These medium and low-voltage distribution networks were originally designed as passive networks to allow power transfer from the transmission network to the end consumer. Distribution networks will contain increasing amounts of distributed generation (DG), which will result in a paradigm shift in the operation of these networks, since the power flow becomes bi-directional and thus active measures such as voltage control using power generation from the PV inverters and automated demand response for increasing self-consumption of PV power during peak hours, among others, should be included [10, 11].

While all these active systems are not yet in place, in the last few years several countries have started the large scale deployment of digital electric meters with bidirectional communication capabilities or *smart meters* in order to measure hourly electricity consumption and transmit the information back to the distribution system operator (DSO) every day and in some cases, in near real time. These, in combination with deregulated electricity markets have provided electricity customers with high contract flexibility and multiple retailer options. For example, residential customers in Sweden can choose different pricing contracts from approximately 200 different retailers, including, in some cases, real-time pricing contracts, where the cost per kWh is determined by the Nordic spot market price.

This brings new possibilities for customers as an active component of distribution networks. Customers can supply power to the network from rooftop PV systems, but in addition, can adjust their own consumption demand based on the output of the PV system (e.g. to maximize self-consumption of electricity) or according to the electricity market spot price. Moreover, customers can make use of demand side management (DSM) automation equipment, such as smart thermostats connected to the spot price and weather forecasts, for controlling the operation of heating systems.

Furthermore, similar technological advances to those that favoured the development of renewable energy technology have also provided a significant boost for the electrification of transportation. For instance, battery technology has improved while its cost has reduced. Similar advances have occurred in power electronics and electric motor technology.

Additionally, primary energy reduction and emission reduction targets have also helped increase the interest in adopting electric vehicles for urban transportation (both private and public). All these new electric vehicles represent itinerant loads that will require a robust and active distributed recharging infrastructure, thus adding extra complexity to the LV distribution network.

1.2 Main Research Question

The main objective of this thesis is to understand the role of the different actors involved in electric distribution systems, and develop simulation models that will enable evaluation of different future scenarios that include large penetration of distributed generation, active customers, demand-side management and the inclusion of new itinerant loads in the system, (e.g. electric vehicles).

1.3 Research Questions

The research questions studied in the included papers were as follows:

1. What are the main advantages for households from adopting hourly spot market electricity pricing agreements? (Paper I)

2. Could households benefit from hourly spot market electricity pricing agreements without adopting demand-side management (DSM) strategies? (Paper I)

3. What are the main impacts on the energy supply system from adopting different energy conservation measures and increasing DG penetration in residential areas? (Paper II)

4. What is the electricity demand impact on detached households in Sweden from using ground-sourced heat pumps? (Paper III)

5. What can be learned from early EV adopters in Sweden, to develop strategies that support the penetration of electric vehicles in other countries and what are the potential impacts on local electric distribution grids from large adoption of EVs? (Paper IV)

6. What are the benefits and challenges from using an equation-based, object-oriented modelling language to model DG components in LV distribution networks? (Paper V)

7. What are the best strategies to integrate DG and e-mobility to increase urban sustainability in mid-sized cities in Sweden and its implications on the existing distribution infrastructure? (Paper VI)

1.4 Structure of the Thesis

The doctoral thesis is comprised of six scientific papers (papers I-VI). The main topic of the thesis is *Active Distribution Networks*, which in turn, is divided in two domains: *Demand Side Management* (DSM) and *Distributed Generation* (DG).

Papers I-IV fall in the domain of *Demand Side Management* (DSM), where the impact on the distribution system was analyzed from the end consumer point of view. Two sub-domains were identified: consumer-based DSM and technology-based DSM, based on the active motivator for DSM. Papers I and IV correspond to the first subdomain, while papers II and III correspond to the second subdomain.

Papers V and VI correspond to the domain of *Distributed Generation*, where the analysis was focused on the interaction between different energy sources and local distribution networks.

A general diagram showing how the papers are related is presented in Figure 1.1.

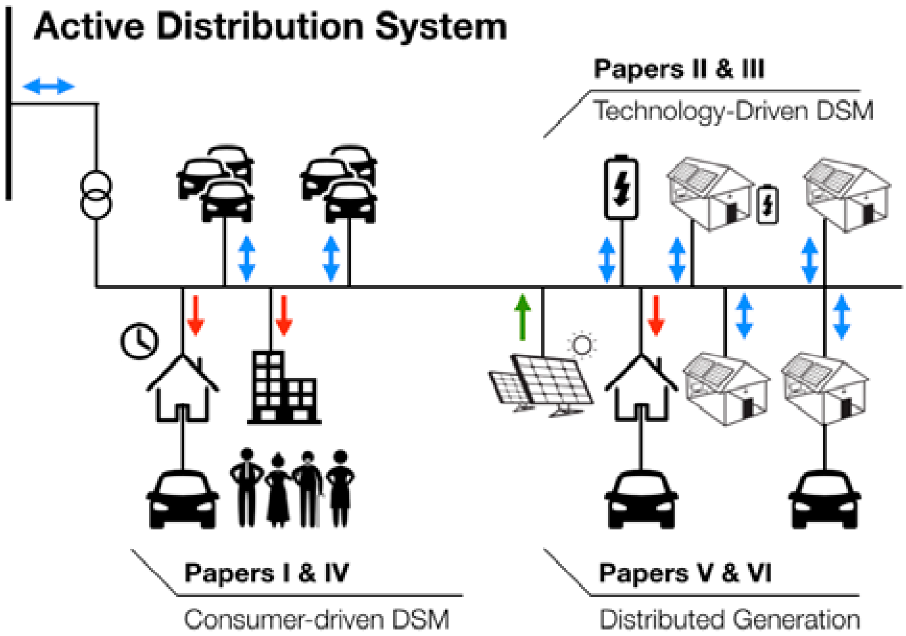

Figure 1.1: Structure of the thesis

Chapter 2

Literature Review

2.1 Active Electric Distribution Networks

The main function of electric distribution networks is to transfer power between the bulk power system and end customers as well as to carry out the required voltage transformations. This section of the power system is also responsible for integrating the power supply from distributed generators and maintaining the voltage levels and power quality within regulatory limits. Consequently, this section of the power system plays the largest role in the power quality perceived by the consumers [12].

More recently, this network has gained a more *active* role and has become responsible for integrating the power production from distributed generators installed across the network. Moreover, further developments are expected, including automated voltage regulation (AVR), extensive use of distributed energy storage devices (e.g. electric vehicle-to-grid concept) and more importantly, bi-directional power flow as shown in Figure 1.1.

The term *smart grid* has also been used extensively to refer to the evolution of electric distribution networks. While both terms can be used interchangeably, *active distribution networks* focus on the integration, operation and control of large penetration of DGs and storage in electric distribution networks. The term *smart grids* is often used to address a larger domain including bulk generation, transmission and the use of advanced monitoring systems (e.g. synchrophasors) for early fault detection that can provide the network with self-healing capabilities to minimize outages.

2.1.1 Main Components

The main components of an active distribution network are [12]:

- Distribution substations
- Primary distribution feeder
- Distribution transformers
- Distribution cabling
- Metering & Control equipment
- Distributed generators

The distribution substation connects the main transmission to the sub-transmission network and converts the HV to MV for use on the primary distribution feeder, where several distribution transformers are connected to convert from MV to LV, suitable for connecting residential and commercial users in the secondary distribution system. This network is connected using a combination of four-wire, three-phase overhead and underground cables according to the required topology and operation voltage and current.

All the variables involved in the operation of the distribution system are measured and monitored in multiple locations across the network; all electric variables (e.g. maximum power, voltage and current, etc.) are continuously measured in the substation, and it is becoming more common to extend the monitoring system down to the distribution transformers, secondary feeders and end-of-line points in order to facilitate outage detection and monitor the power quality on the entire network at all times. Moreover, changes in metering requirements from electricity market regulations, increased contract flexibility and the reduced cost of micro-controllers and communication technologies have made it possible to deploy automated meter reading (AMR) systems where power and energy usage is measured and recorded at every consumption point in real time.

While the primary purpose of AMR is for billing, several authors have suggested using the additional capabilities of the infrastructure to provide operational data in real time from each consumption point for online diagnostics, outage detection and network management [13, 14, 15].

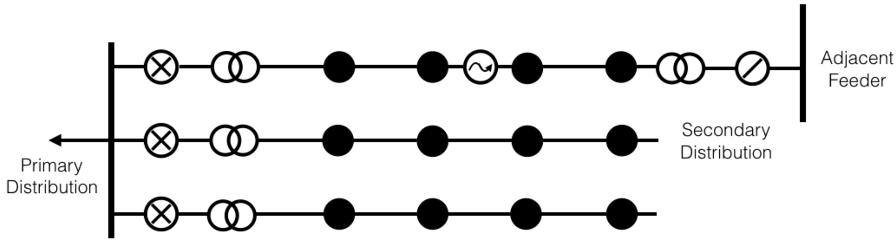

Figure 2.1: Radial topology

2.1.2 Topologies

In secondary distribution networks operating at LV, overhead and underground lines connect end consumers with primary MV feeders through distribution transformers, switches, section breakers and other equipment, mounted on poles or in distribution cabinets. The most common topologies used in these distribution systems are radial, loop and several combinations of both [12].

Radial Topology: This topology is the simplest and most economical, and is often used in low-density areas (e.g rural distribution networks). Its main limitation is that in case of failure in any point of the network, all the customers connected to the branch would suffer a power outage. In order to reduce the duration of interruptions, automatic reclosers can be used along the network together with sectionalizing fuses on branches, to allow unaffected sections to remain in service in case of temporary failure. A simple radial topology is shown in figure 2.1. More complex radial feeder models are presented by Kersting et al. [16].

Loop Topology: Loop topologies offer a higher level of service reliability, but also require the use of redundant equipment which can make it more expensive to implement. In its most basic form, two feeders form a closed loop, open at one point so that in case of a failure, the sectionalizer switch closes in one location while another opens at a different location. This topology offers higher reliability and it is commonly used in urban MV distribution networks and some LV networks in dense residential and commercial areas. A diagram of this topology is shown in Figure 2.2.

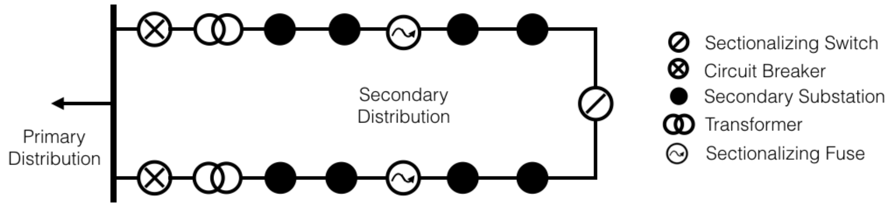

Figure 2.2: Loop topology

2.1.3 Network Operation and Control

The distribution system was designed to operate as a perfectly balanced three-phase system. This means that the voltage of each phase is equal in magnitude but 120 degrees out of phase from the others. In reality, unbalanced loads, large penetration of DG, power electronics and other components connected to the network introduce perturbations that require the use of active and passive components to maintain the system operation as close to nominal conditions as possible. When these conditions are not met, the reduction in power quality can affect satisfactory operation of the network components (e.g. overheating of transformers, faulty tripping, etc.) as well as customers' equipment (e.g. faulty operation of heat pumps).

Voltage is one of the parameters that has to be controlled and maintained within a narrow operating range. In Europe and the US, the voltage levels in primary and secondary distribution networks should be maintained within $\pm$ 5% - 10%, based on national regulations [17, 18].

Several voltage control techniques are typically used. For instance, the DSO regulates the primary voltage at the substation and the feeder that connects to the first group of customers, usually by employing tap changers in the transformers that connect the primary and secondary distribution levels. These tap changers can be changed manually (for seasonal load variations) or automatically (using automatic voltage regulators, AVRs). Furthermore, if AVRs are not sufficient, shunt capacitors are installed in order to provide the additional reactive power required to maintain the operation voltage within the required limits. Lately, a large penetration of inverters from DG has introduced additional voltage fluctuations that were not originally accounted for. For instance, in networks designed to control the voltage operation using AVRs, large penetration of DG and the increased demand from electric vehicles (EVs) have forced AVRs to switch hundreds of times per day, instead of just a few times as they were designed for. This has caused some of these systems to reduce their operation lifetime substantially [19].

Consequently, in large distribution networks with large penetration of DG and EVs, AVR and shunt capacitors alone may no longer be sufficient to provide the required support to maintain the operation voltage within the required limits. Fortunately, the same equipment that has introduced these perturbances can also help mitigate them. Several authors have investigated the potential use of the PV systems inverters' capabilities to inject reactive power into the system, in order to provide the required support to maintain its operation within the required limits [20, 10, 21, 22]. Therefore, new active distribution networks need to use these capabilities to maintain the networks' reliability, as well as to allow larger DG penetration. On the demand side, new technologies can also provide grid support by controlling their demand according to the network's operation conditions. On one hand, building automation technologies (e.g. lighting control, smart thermostats, etc.) can adjust their operation in response to weather forecasts, price signals or simply network signals. On the other, EVs can control their charging process, according to the network's capacity, and in some cases, supply power from the batteries in what is known as vehicle-to-grid (V2G) operation.

2.2 Distributed Generation

Distributed generators (DG) produce energy locally and can use either conventional or renewable energy technologies. Several reasons motivate their wide adoption: DG increases distribution efficiency by reducing the distance and power conversions between production and consumption; it can also help postpone upgrades on the existing grid by increasing the locally available power capacity; but ultimately, the strongest motivator for large DG adoption is their ability to effectively integrate renewable energy technologies, with the environmental advantages they offer, such as the reduction of greenhouse gases (SOx, NOx, CO2), pollution reduction from large production plants as well as reduced environmental impact for extraction, refining and transportation of fossil fuels [23].

2.2.1 Solar Photovoltaic

Solar photovoltaic (PV) is a technology that converts light directly into electricity. The individual photovoltaic element is the solar cell, which is made out of semiconductor materials.

Depending on their power output capacity, solar PV system installations can be classified as utility scale or commercial/residential. The former are characterized by being centralized and offering large power output capacities (>1MWp), and are often connected to the transmission grid at MV or HV. Residential and commercial installations offer smaller power output capacities (<20kWp for residential and <1MWp for commercial) and are scattered, usually located close to the consumption loads and directly connected to LV or MV distribution networks.

2.2.2 Micro-gas turbines

Micro-gas turbines are small energy generators usually ranging from 15 to 300 kWe, and are based on the standalone joule cycle [24]. Micro-gas turbines are commonly used as backup generators, with an average fuel to electricity conversion efficiency between 22-30%, although several models can operate in combined heat-and-power (CHP) mode to produce both electricity and heat, increasing the overall efficiency to over 80%. This characteristic makes them very attractive for applications where both electricity and heat are required, for instance in residential neighbourhoods, hospitals, commercial facilities, etc. In general, micro-gas turbines offer several advantages, for instance: high-speed operation, high reliability, low maintenance and low NOx emissions [25].

2.3 Demand side Management

Demand side management usually refers to changes on the consumption side of the network in response to requests from the system's operator, for instance, to shut off non critical loads during peak power consumption times. However, newly introduced flexible pricing contracts offer customers the possibility to voluntarily modify their electricity consumption patterns in response to changes in the market by shifting heavy consumption loads to low-cost times.

2.3.1 Electricity Markets

Different power sources have to be dispatched based on demand fluctuations in order to maintain the balance between load and supply at all times. Each power source has a different cost structure and runs under different operation conditions. The transmission system operators (TSOs) and balance providers decide which power sources to include in the system at any given time based on several parameters: running costs, electricity demand forecast, weather conditions and reservoir capacities.

These power production costs are highly variable and thus, effective ways to charge end users for a product that is highly variable in nature, has been debated since the beginning of the electric power industry itself. DSOs defined the optimal pricing regime for this service as Hopkinson's differentiated rates based on time-of-day use [26] and since then, additional dynamic pricing schemes have been developed. Today, different pricing methods include critical peak pricing (CPP), critical peak rebate (CPR), demand based tariff and real time pricing (RTP) [27, 28, 29, 30, 31].

In Scandinavia, the electricity market was deregulated on January 1 1996, meaning that both electricity production and retail have been subject to competition since the reform. The wholesale price of electricity is determined by supply and demand on an hourly basis on NordPool's spot market (Elspot) for the next 24 hour period. Due to physical transmission restrictions between countries, the Nordic electricity market is divided into bidding areas (Elspot areas) [32]. The network operation still remains as a regulated monopoly in Sweden. The distribution networks are operated by about 160 different distribution system operators and the transmission network is governed and operated by Svenska Kraftnät, the Swedish TSO.

For each hour of the following day, the players in the spot market specify the amount of electricity they wish to sell or buy. All the bids are aggregated both as price and quantities and the demand curve is built from the sum of all purchase bids. The combination of price and quantities where supply and demand curves match establish the market price as shown in Figure 2.3 [32].

NordPool Spot's market share of all the electricity traded in the Nordic and Baltic area in 2014 was 501 TWh [33], the largest part of all the electricity produced and consumed in the area. In Sweden, the total electricity produced in 2014 was 149.5 TWh, with a net export of 10 TWh, leaving a total of 139.5 TWh of electricity for domestic use [34]. Almost all electricity generated and consumed in Sweden was traded through NordPool Spot.

2.3.2 Smart Metering

Smart meters are electronic devices that measure and record electricity consumption mainly for billing purposes. Most modern smart meters offer two-way communication capabilities to send electricity consumption

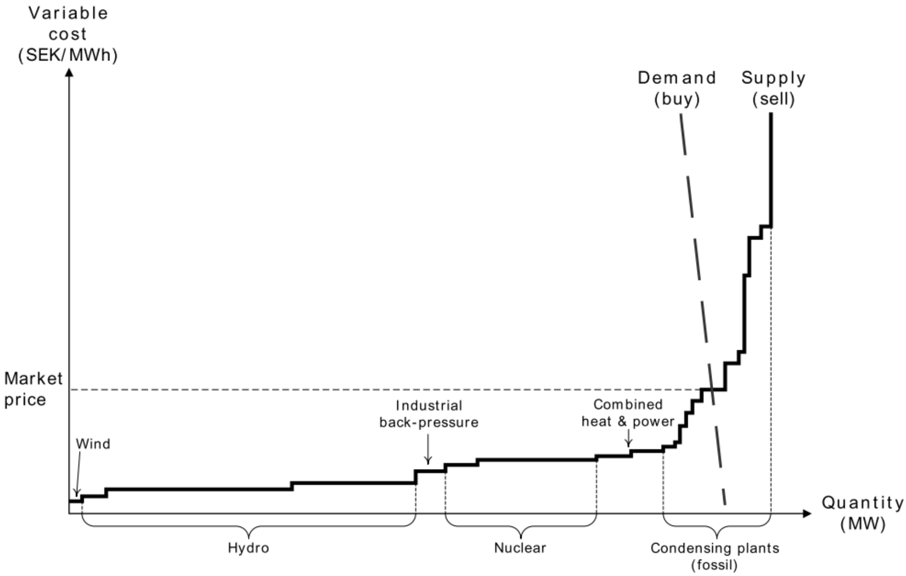

Figure 2.3: Price formation in the Nordpool Spot Market

and production (e.g with installed PV systems) information back to the DSO, as well as additional parameters (e.g. power quality, alarms, etc.) that can be used for advanced network monitoring.

2.3.3 Variable Electricity Pricing

Variable pricing schemes are implemented to encourage users to shift power consumption from peak use to lower use times, in order to help balance the load in the power system. This is accomplished by applying dynamic pricing mechanisms that are closer to the real cost of electricity supply. The most common methods are: monthly variable pricing, where the cost per kWh is based on the electricity spot market average price for the month; Time-of-Use (TOU), where two or more tariffs are used for high peak and low peak times; Critical Peak Pricing (CPP), where a flat rate is used unless there is a high peak critical situation when a very high price per kWh is applied; Critical Peak Rebate (CPR), where users are paid to lower their consumption under critical peak times; and Real Time Pricing (RTP), where an hourly spot market price is applied.

One of the main advantages for residential users of a deregulated market together with smart metering technology is the contract flexibility and options provided by electricity retailers [35]. Residential customers in Sweden can choose different pricing contracts from approximately 200 different suppliers. The most common types of contracts chosen by the customers are: variable pricing contract, where the cost per kWh is based on NordPool Spot's monthly average spot price plus a retailer fee; fixed price contract, where the user pays a predetermined electricity price agreed between the retailer and the customer which remains fixed for the duration of the contract (1, 2 and 3 years); default contract, which is selected by the local network owner if the customer does not make an active choice; hourly RTP, where the cost per kWh is determined by the spot market price; other contracts options include demand based pricing options and mixed rates (e.g 50% fixed, 50% variable) [36].

2.3.4 Demand side Management Strategies

Examples of DSM strategies include: conservative voltage regulation (CVR), where the operation voltage in secondary distribution networks is reduced to minimize losses and the energy demand in the system; smart appliance controllers that react to electricity market prices and only operate during low-price hours; and the use of building automation and control systems (BACS), due to their great potential to adjust the buildings' power consumption in real time.

BACS apply the principles of linear control theory to monitor and efficiently control the equipment that interacts with the multiple subsystems involved in building operations. Modern BACS make strong use of communication technologies, and more recently, use wireless sensors that provide real time variable monitoring, which combined with real time electricity price information and energy management systems (EMS), provide great opportunities for optimizing the buildings' energy usage in real time.

Other demand side management strategies include the use of smart thermostats for the operation of heating systems; residential EMS; controlled charging mechanisms for EVs and the participation of active electricity customers with great awareness and knowledge about the impact of their activities on energy consumption to react and make demand changes when required.

2.3.5 Heat Pumps

Heat pumps transfer heat from a low temperature source to a high temperature source by heating and compressing a refrigerant with a low temperature boiling point. The heat from the refrigerant is transferred to the heat sink using a heat exchanger where the refrigerant is condensed back to liquid form.

A particular type of heat pumps is the ground sourced heat pump (GSHP), which can achieve a 1:3 electricity to heat conversion ratio [37]. This means that from 1 unit of electricity it is possible to obtain 3 units of heat. Consequently, its growth facilitates the reduction not only of fossil based heating, but also direct electric heating, increasing the overall electricity to heat conversion.

In Sweden, installations of GSHP have been steadily increasing over several years, up to the point that the country boasts the largest number of GSHPs installed in Europe.

2.3.6 Electric Vehicles

In conventional vehicles, fuels with very high energy density (mainly hydrocarbons) are stored in a tank and burned in an internal combustion engine to produce the required power to provide the vehicle's propulsion. In an electric vehicle, an electric motor is used to provide the required propulsion, and takes the required energy from an onboard electrochemical or electrostatic energy storage device [38].

Typically, the term EV is used indistinctly to refer to plug-in hybrid electric vehicles (PHEV), extended range battery electric vehicles, battery electric vehicles and hybrid electric vehicles.

The two major battery technologies used in electric vehicles today are metal hydride (NiMH) and Li-ion. Most PHEV available in the market have used NiMH because it is a more mature technology. However, thanks to the higher specific energy and energy density, the adoption of Li-ion technology is increasing in all EV types [39].

The battery capacity determines a vehicle's driving range: a large battery provides a long range at the expense of lower overall efficiency (due to the increased weight) and a higher capital cost. Conversely, a small battery may not increase the vehicle's weight significantly, but if it does not provide the required range, it may not be worth the extra cost and weight of the electric motors and power electronics.

The increased number of EVs can severely affect existing electricity consumption profiles by increasing the evening peak which, according to a survey carried out among private EV owners in Sweden, is when customers are most likely to charge their vehicles. Masum et al [40] investigated this consumption peak increase on a 1200 node test system topology and found out that voltage violations would occur during the night peak with EV penetrations as low as 17%. Furthermore, a simulated EV penetration of 62% (the maximum penetration simulated) would increase total distribution losses by 500%.

Most EVs currently on the market use batteries with capacities that vary between 12 and 24 kWh, which provides an average driving range of about 160 km [41]. In Europe, however, the average EV owner drives a considerable shorter distance daily [42]. Furthermore, common driving patterns show that most private EVs spent the majority of the time parked, thus opening new possibilities for vehicle-to-grid (V2G) integration schemes. A large distributed energy storage network can allow larger penetration of DGs without the need for additional upgrades of the distribution network's capacity since excess power could be stored in the vehicle's batteries to be used at peak time.

2.4 Mathematical Modelling

Mathematical modelling allows us to represent the behaviour of a physical system with a set of equations, so that a specific set of experiments can be simulated on a virtual system rather than on a real one.

There are several reasons to perform simulations instead of carrying out experiments on real systems. For instance, it can be too expensive or too dangerous (e.g. testing different operation conditions on a nuclear power plant); the system that we want to conduct experiments on may not yet exist (e.g. a new blade design for a wind turbine); the time scale of the system is not compatible with that of the experimenter (e.g. celestial objects trajectory analysis); and more freedom to manipulate the variables of the model, among others.

2.4.1 Modelica Language

Developed in 1996, Modelica is an non-proprietary, open source, object-oriented language for modelling large, complex, and heterogeneous physical systems. The language uses mathematical equations and object-oriented constructs to facilitate the reuse of models, which allows effective library development and model exchanges [43].

Unlike specialized simulation tools, the Modelica language is suited for multi-domain modelling such as complex systems that involve mechanical, hydraulic, electric, state machines, process control etc. Such systems can be built together into a single model by using the appropriate algebraic equations that represent the physical behaviour of each subsystem.

Modelica is based on equations instead of assignment statements, which means that it allows for acausal modelling, because equations do not define a specific data flow direction and the global equation system is solved simultaneously.

2.4.2 Power Systems Modelling in Modelica

In Modelica, models are mathematically described by differential, algebraic and discrete equations. Variables do not need to be solved manually and unlike modelling and simulation languages that use sequential solving, Modelica allows simultaneous equation solving of large, complex equation systems. This ability facilitates the process of prototyping and testing models.

This approach allows easily reusing models, since each model is defined as a set of equations. When connected together with other models, Modelica's compiler puts all the equations together, extracts the unknown variables and known parameters, and optimizes the simultaneous solving process automatically.

Moreover, Modelica's open source standard library contains about 1280 model components and 910 functions from multiple domains, to provide a set of models that help develop larger and more complex physical systems [44].

The complexity of power systems and their associated dynamics require the use of robust modelling and simulation tools. Several approaches have been used in the past, from using simplified numerical methods to complex specialized transient analysis software packages that use proprietary code. This approach has led to inconsistencies between different simulation and modelling methods from different platforms. Equation-based languages allow for model exchange and unambiguous modelling and simulation across different platforms [45]. Moreover, by representing models with their equivalent mathematical equations, it becomes easier to understand the systems' dynamics, to modify and reuse models, and build more complex systems on a common standard modelling language.

Chapter 3

Methodology

3.1 Demographic and Consumer-related Data

A survey was sent out in a residential area of the Sollentuna municipality in Sweden. The questionnaire was sent out to 735 households and comprised of 37 questions regarding housing and energy consumption characteristics. A total of 528 households responded, from which a group of 322 (response rate of 43%) was selected, made up of households with GSHP installed at least four years before the survey. The information from the survey was tabulated and analyzed in order to classify households and extract characteristics as well as to find patterns. This information is presented in papers I and III.

In paper IV, a paper survey was developed and sent out to electric vehicle owners registered as private users in Sweden. A total of 399 surveys were sent out in March 2015, and after a period of 3 weeks, 247 responses had been received, a response rate of 62%. The survey contained several questions with free text answers (e.g. average income) although the majority of the questions consisted of multiple-choice answers. The questions included in the survey could be divided into four different groups. The first group comprised of questions regarding the drivers personal and household characteristics; the second group of questions targeted the EV drivers motivation and use of their electric vehicle; the third group of question was intended to gather information on EV drivers driving and charging patterns; the last group targeted information about the technical specifications of the EVs.

3.2 Case Studies

In paper II, five case studies were carried out in which different energy conservation measures (ECMs) were implemented in building renovations in Sweden. These cases were selected based on the data available for the projects, technologies used, ECMs impact on the energy supply network and the populations in the cities where the projects were carried out.

In paper VI, the energy goals and actions established by the municipality of Eskilstuna in Sweden were evaluated, with special focus on the use and integration of renewable energy sources (mainly wind and PV), transport and the building sector. The evaluation used data provided by the local municipality and was complemented with simulation models.

3.3 Electricity Consumption & Pricing Data

The electricity consumption data between 2001 and 2007 used in papers I and III was obtained from the local distribution system operator (DSO), who provided access to the automatic meter reading (AMR) data from the Sollentuna area. For each customer and measurement, each row in the dataset contained the meter identification (ID), time stamp (YY:MM:DD HH:MM) and hourly electricity consumption value (in kWh). Additionally, information about the main energy source used for heating was also provided for each user ID. There were two main user groups: those connected to the district heating (DH) network and those that used ground sourced heat pumps (GSHP) as their main heating source.

Spot-based electricity price data for real time pricing (RTP) contracts cost calculation was obtained directly from NordPool's database for Elspot's prices of the physical market area. Hourly electricity values for the 4 bidding areas in Sweden were available at 1 hour intervals.

Fixed electricity prices of one year contracts for each customer group type (DH or with GSHP) were obtained from Statistics Sweden (SCB) [46].

3.4 Modelling & Simulation

In paper V, two models were developed using the Modelica language for two generators of the Savona's Polygeneration Microgrid (SPM) laboratory from the University of Genoa in Italy. The first generator was a 65 kWe integrated combined heat and power (ICHP) natural gas microturbine, and the second was a 49 kWp roof-mounted PV system.

The first model was developed in a top-down scheme using the manufacturers data to build the equation system. From the basic equation system, different performance derating curves were added from the manufacturer's data [47] in order to determine the microturbines maximum performance under different operation conditions (outdoor temperature, humidity, altitude, etc.). The second model used the equivalent electric circuit model proposed by Sera and Teodorescu [48] for a photovoltaic cell. The hourly solar irradiance required in the model was composed of the main, diffuse and ground-reflected beams; the main beam was calculated from the equation models proposed by Mehleri et al. [49] and neither the diffuse nor ground-reflected beams were included.

The validation dataset for the ICHP consisted of 3997 1 min resolution operation data points. The validation dataset for the PV system consisted of 8865 operation data points at the same resolution. Both were taken from the SPM's energy management system SCADA. Weather data was obtained from the nearest weather station to the campus, located 15 kilometers north-west of Savona, where the SPM was located.

In paper IV, the survey information was used in combination with a simulation model developed in Dymola using Modelica language to estimate the impact of larger adoption of EVs on local distribution networks. The mathematical equations used to build the EV battery model and charging mechanism were obtained from the battery models presented in [39, 50, 51, 52].

3.5 Data Processing

In papers I and III, the hourly electricity consumption entries were formatted into MATLAB time series for processing and any missing values were linearly interpolated. Each user's time series was adjusted for daylight saving time (DST) for each year and all data entries were indexed using a common time vector. This vector was formatted in a serial data format that represents, in a single number, the amount of time that has passed since 01/01/0000 to facilitate the data compilation for all customers into a single matrix.

To calculate each individual customer's electricity costs in the case of a fixed price contract, the fixed cost was determined by the annual electricity usage, therefore, customers with GSHP had lower cost per kWh. In the case of RTP, electricity costs were calculated by multiplying the hourly electricity consumption matrix and the spot price matrix to obtain a new matrix representing the hourly costs. Monthly and annual electricity costs were calculated from the hourly costs matrix. The hourly electricity price was the same for every customer, regardless of whether the customer used electric heating or they were connected to the district heating network.

In addition to the electricity supply cost, the network charge, retailer fee, electricity tax and VAT were added and calculated monthly for every customer during the studied time period.

The network charge depends on the customer's fuse size and peak demand. Therefore, this charge was calculated by estimating the fuse size from the historical peak power consumed over the 7 year period, extracting the maximum current at an average power factor of 0.85. This is explained in more detail in paper I.

While the retailer fee for fixed price contracts was included in the cost per kWh, the fee for RTP contracts was obtained from the ten companies in Sweden that offered this service as of March 11th 2014 and added to the calculation of the cost per kWh.

Electricity tax for the seven year studied period was obtained from Svensk Energy [53] and VAT of 25% was added to the total for each customer.

The general equations used for both fixed and RTP contracts are shown in equations 3.1 and 3.2.

$$Elcost_{Fixed} = (E_{kWh} * (N + T)) * (1 + VAT) \tag{3.1}$$

$$Elcost_{RTP} = (Eh_{kWh} * RTP + E_{kWh} * N + Rf) * (1 + VAT) \tag{3.2}$$

Where:

$Elcost_{Fixed}$	= Monthly electricity cost in SEK
$Elcost_{RTP}$	= Monthly electricity cost in SEK
E_{kWh}	= Monthly electricity consumption in kWh
Eh_{kWh}	= Hourly electricity consumption vector in kWh
RTP	= RTP vector in SEK/kWh for every hour of the month
Rf	= Monthly retailer fee
N	= Network tariff in SEK/kWh
T	= Fixed fee tariff in SEK/kWh incl. the retailer fee
VAT	= Value added tax

The datasets used for validating both generator models used in paper V had its timestamps synchronized with the weather data samples in order to simulate all components with the same time steps. Additionally, each atasets was formatted in a 2-dimension table (timestamp, data) to be imported and used in Modelica.

Chapter 4

Results and Discussion

4.1 Electricity Demand

4.1.1 Heat Pumps

The results presented in paper III show that the majority of households had their own heating system (e.g. not connected to the district heating network) before the GSHP installation. Only 10% of the respondents had heat pumps before the year of installation (23 households had GSHP while 9 had air-air heat pumps). During the period when the questionnaire was sent, 320 households had GSHP installed while 12 had air-air heat pumps.

Cost Analysis

The average investment made by the homeowners was 120150 SEK (13000 EUR) (N=208) for a new GSHP system. When comparing the operation costs between DH and GSHP, the former are more expensive to run during March and April, while the latter are more expensive to run between October and February. While this makes GSHP a better alternative in a one year analysis, GSHPs have a limited lifetime while DH does not require new investments, which would make it more economical in the long run unless electricity prices are low and smart thermostats are used to operate the GSHP to reduce its operation costs even further.

The average annual electricity consumption for households with DH and GSHP during the studied period are shown in Figure 4.1.

Results revealed that the minimum additional electricity consumption for GSHP-based households was 11.9% in 2002, and the maximum additional electricity consumption was 76.5% in 2006, when the highest

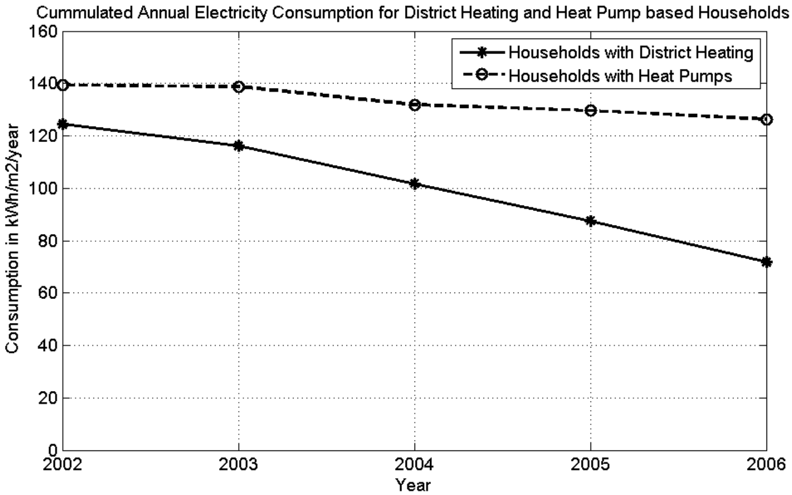

Figure 4.1: Annual electricity consumption for DH-based households and GSHP-based households.

number of continuous sub-zero temperature days of the 5 year study period also took place.

Additionally, it was found that the annual consumption for GSHP-based households was more stable over the 5 year period with an average of 133.2 kWh/m^2/year. Households using DH experienced a continuous decrease in electricity consumption from 124.4 kWh/m^2/year in 2002 to 71.76 kWh/m^2/year in 2006, a reduction of almost 43% due to investments in energy efficient lighting and appliances, according to the answers in the questionnaire.

The monthly electricity consumption was compared between DH-based and GSHP-based households over the 5 year period. Results are shown in Figure 4.2.

The monthly analysis provided more detailed information about the temperature impact on households with GSHP compared to those with DH. The difference in electricity consumption between DH and GSHP based households was very small during the Spring and Autumn months, when nearly no heating or cooling is required. However the difference was larger during the other seasons, particularly during Winter.

The Winter of 2003 had the lowest average temperature of the 5 years analysed, and therefore had the greatest impact on the electricity use of GSHP based households. In contrast, the winter of 2005 was the warmest and consequently, the electricity use was lowest.

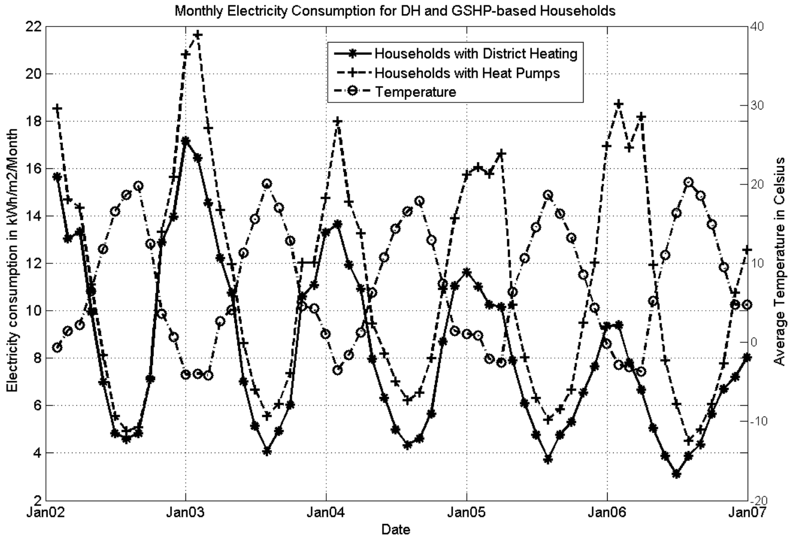

Figure 4.2: Monthly electricity consumption for DH and GSHP-based households

An interesting case occurred during the winter of 2006. Although the temperatures recorded were not the lowest, the average temperature was exceptionally low from December 2005 to February 2006. This resulted in high electricity use from households with GSHP over a longer period of time. Although the spike was not as high as the one experienced in 2003, it caused a higher overall electricity consumption for the whole season. The summer of 2006 was the warmest summer, and therefore electricity use was the lowest, balancing the overall annual consumption.

It was observed that even a slight change in the average temperature during the cold months could cause a dramatic change in the energy use, especially with continuous sub-zero temperature days, when GSHP operation efficiency is lowest.

4.1.2 Impact on the Energy Supply System

In paper II, the adoption of different energy conservation measures (ECMs) as well as DG penetration were evaluated from different case study reports in order to analyze the impacts not only on the buildings where these measures and DG were adopted, but also on the energy supply network.

In the first case report, seven different ECMs were simulated. Results showed that when residual biomass fuels (e.g. waste) are used in the DH system, reducing electricity consumption and improving the buildings' envelopes are the only favourable ECMs for improving primary energy efficiency and reducing GHGs.

The second case report studied installing rooftop PV systems on buildings combined with energy storage systems. The results indicated that using electric storage systems provided the highest level of PV self-consumption, but also offered the highest levelized cost of electricity; while using heat storage provided similar self-consumption levels with almost half of the levelized cost of electricity.

The third case evaluated a renovation project carried out in Allingsås, Sweden, where 16 buildings were renovated using different ECMs to bring them to near-zero passive building standards. The investment costs varied between 133-570 /m2 and the calculated energy consumption savings ranged between 62-85%.

The fourth case study report presented consumer driven ECMs. Results showed that it is possible to reduce energy consumption by up to 33%. However, whether the savings would remain without periodic follow-up from energy efficiency advisors is uncertain.

The fifth case study report considered electricity usage in households with GSHP and variable-pricing electricity contracts. It concluded that while GSHP is the best option for detached households, it is important to consider electricity price fluctuations during the Winter season when GSHP requires the highest amount of electricity. The adoption of smart thermostats or energy management systems (EMS) was therefore recommended.

In general, results from the case studies showed the importance of considering the characteristics of existing energy supply networks around the buildings where ECMs are adopted, in order to select the strategies that provide the greatest benefits both for the buildings and the energy supply system.

4.2 Opportunities from Electricity RTP

In paper I, the impact on electricity bills after switching from a fixed price per kWh contract to RTP was studied for 400 households (200 connected to the DH network and 200 with HP).

Results for the 7 year period analysis are shown in Figure 4.3 for users connected to the DH network and in Figure 4.4 for users with HP, together with the monthly average temperature. In the figures, the

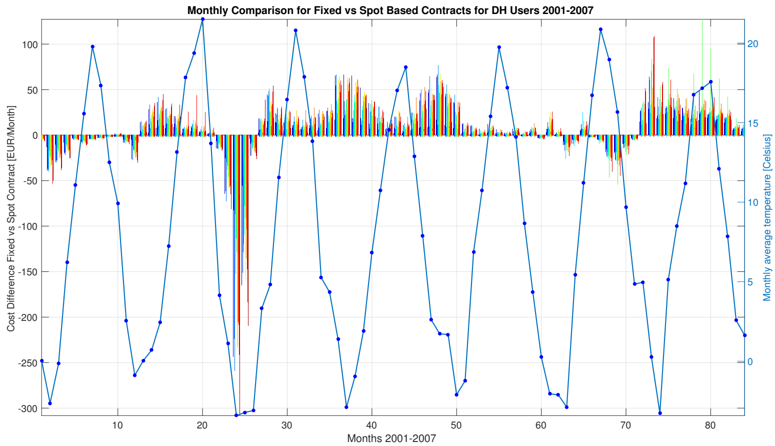

Figure 4.3: Monthly cost difference between pricing contracts 2001-2007 for customers with District Heating

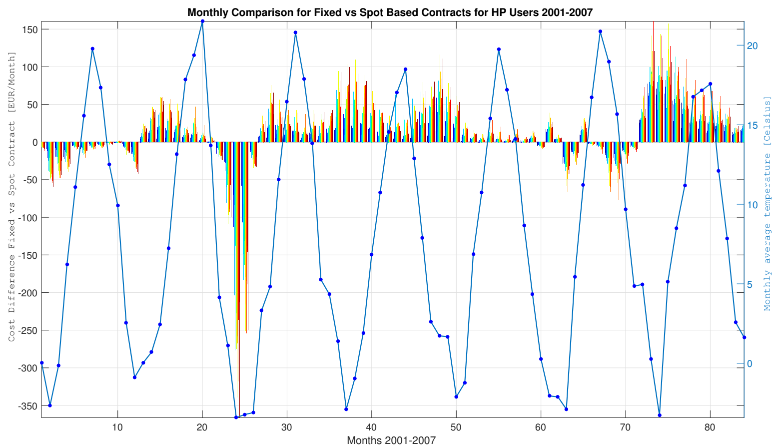

Figure 4.4: Monthly cost difference between pricing contracts 2001-2007 for customers with Heat Pumps

plots show a positive value for each month when RTP contract offers a lower price. A negative value is shown when the RTP contract is more expensive.

While both figures follow the same trend, customers with HP experienced larger fluctuations, on both the positive y-axis (more economical

Table 4.1: Electricity consumption peak times

	Morning Peak		**Afternoon Peak**	
	DH Users	HP Users	DH Users	HP Users
2001	9:00	9:00	20:00	20:00
2002	9:00	9:00	20:00	20:00
2003	9:00	9:00	20:00	20:00
2004	9:00	9:00	21:00	20:00
2005	9:00	9:00	21:00	21:00
2006	9:00	9:00	21:00	21:00
2007	9:00	9:00	20:00	21:00

for RTP) and on the negative y-axis (more economical for 1 year fixed price).

4.2.1 Electricity Time of Use (TOU)

Regarding time of use of electricity, it was found that morning consumption patterns were similar, peaking at 9:00 am every day (on average for all consumers) for all years of the studied period. The afternoon peak hour differed between user groups and between different years. Users connected to the district heating network experienced an afternoon peak at 20:00 for four out of seven years (57%) analyzed in the study, and at 21:00 for the remaining three years (43%). However, the overall electricity consumption was very similar during these two hours. The result was the same for users with heat pumps, although the peak hour time differed between years when compared to the other users group. Electricity TOU for every year are shown in Table 4.1.

In the electricity market, the spot price experienced its highest price of the day at 9:00 am for five out of the seven years of the study (72%), at 12:00 pm for one year (14%), and at 18:00 for one year (14%). The annual average hourly price per day was at noon for four years (57%), at 09:00 for two years (28.5%) and at 11:00 for one year (14.5%).

The results suggest that the strongest impact on residential electricity costs was caused by the morning consumption peak, since it occurred at 9:00 am when the electricity price was most frequently the highest of the day. The afternoon consumption peak had less impact on the electricity cost since it occurred between 20:00 and 21:00, when the electricity price was low.

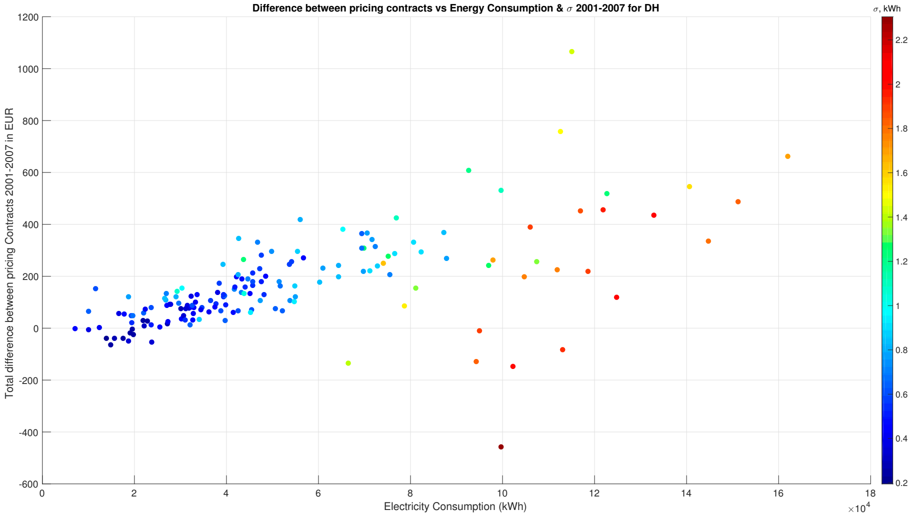

Figure 4.5: Total cost difference between pricing contracts 2001-2007 for DH

4.2.2 Annual Analysis

Results obtained from the 7 year period showed that for most consumers in both user groups it was more economical to adopt a RTP contract instead of a 1 year fixed price contract. Although the end result looks scattered in Figures 4.5 and 4.6, the average savings for DH users was 162,3 EUR and 569 EUR for HP users, both in favour of RTP (positive side of the axis). A maximum of 1551 EUR in savings was obtained in the HP user group and 1066 EUR in the DH user group. There were only two users (2,6%) in the HP group and seventeen (10,4%) in the DH group for which the RTP contract was more expensive. The largest price difference in favour of the 1 year fixed price contract was 84 EUR in the HP group and 458 EUR in the DH group.

Two correlation coefficients were obtained in order to determine the relationship between the cost difference and the customers' consumption standard deviation (σ), and between the cost difference and the annual energy usage. These coefficients were defined using the Pearson correlation coefficient [54] for N scalar observations, calculated as follows:

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\overline{A_i - \mu_A}}{\sigma_A}\right)\left(\frac{B_i - \mu_B}{\sigma_B}\right) \tag{4.1}$$

Where μ_A and σ_A are the mean and standard deviation of A, and

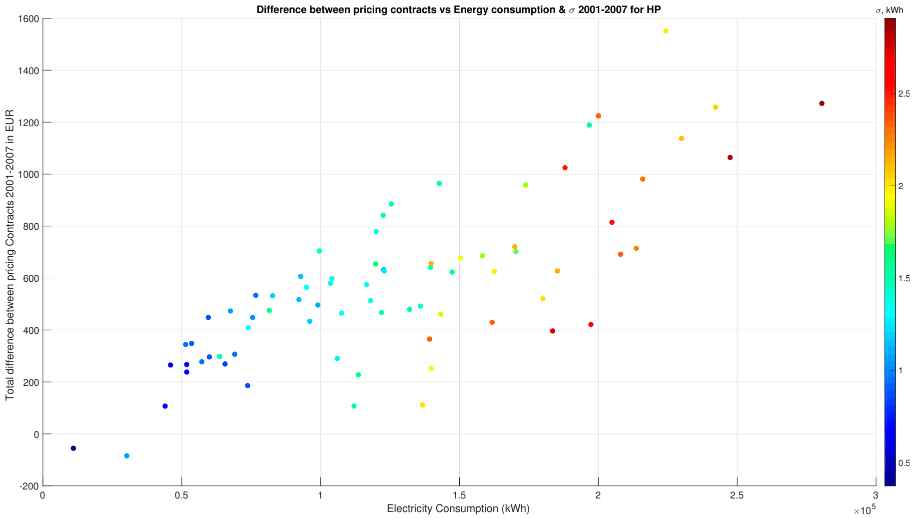

Figure 4.6: Total cost difference between pricing contracts 2001-2007 for HP

μ_B and σ_B are the mean and standard deviation of B.

Results are shown in Figure 4.7. In years with large differences between the 1 year fixed price contract cost and RTP (i.e. 2001, 2004, 2005 and 2007) there was a high correlation coefficient between the cost difference and annual usage. Years with high price variability (e.g. 2002, 2003 and 2006) had lower correlation coefficients between the cost difference between contracts and the annual energy usage. The correlation coefficient with consumers' standard deviation (σ) was found to be generally lower than the correlation with annual energy usage, but they both followed the same general trend. Likewise, a positive correlation coefficient resulted in positive average cost in favour of RTP, while a negative correlation coefficient meant that 1 year fixed contracts were more favorable for users in both groups. However, when the correlation coefficient was positive, the cost difference was considerably higher in favour of RTP.

4.3 Electric Vehicles Adoption in Sweden

From the survey results presented in paper IV, it was found that the majority of EV owners in Sweden live in houses outside densely populated areas. One reason for this is the lack of charging infrastructure within city perimeters. Additionally, there is a lack of general support

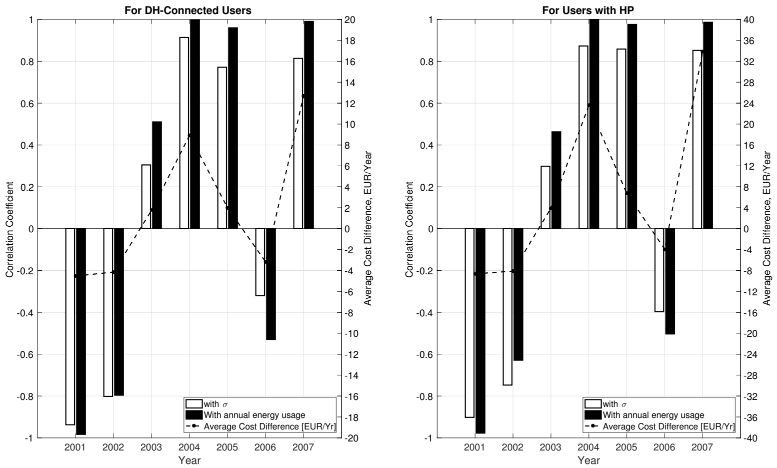

Figure 4.7: Correlation between cost difference with standard deviation and annual energy usage

for charging points besides the funding provided for R&D [55]. Analyzing existing charging locations and the time of the day when electric vehicles are charged plays an important role in the preparation for scenarios with high EV market penetration.

The majority of the respondents (64%) drive their electric vehicle for distances between 30 and 100 km/day. Moreover, 173 (70%) of the EV owners stated that they only charge their vehicles at home; while 12 (5%) use the charging spots at their work places. Only 1% of the respondents charge their vehicles while doing errands and the majority of the EV owners charge their cars at night; 57% during weekdays, and 62% during the weekend.

The total number of EVs that are connected to the grid in Sweden is expected to reach approximately 18 000 at the end of 2016 [56] and 162 500 in 2030 [57]. While the overall electricity consumption increase could be met by Sweden's generation capacity projections of 175 TWh by 2030 [58], the increased number of EVs can severely affect today's electricity consumption profile by increasing the evening peak, which, according to the survey carried out in this paper, is when the survey respondents state that they charge their cars. This peak increase, in combination with existing available variable pricing schemes (real time pricing and demand based pricing) could lead to a system peak that requires the use of fossil fueled peaking power plants. The use of these power stations

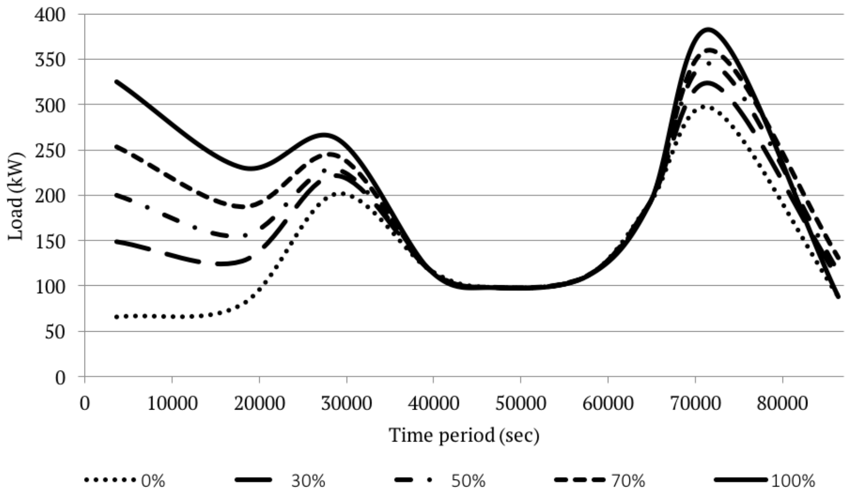

Figure 4.8: Load increase with different levels of EV penetration

increases the CO_2/kWh in the electricity mix, and consequently the running cost per km of EVs due to an increased system electricity price.

Results obtained from the simulation model built in Dymola using Modelica language showed that with the majority of vehicles charging at night at home (corresponding to the residential evening consumption peak), voltage violations occurred with EV penetration levels over 30% and losses in the LV distribution network increased significantly, as shown in Figure 4.8. These results are similar to those found by Masum et al. [40], who suggested that scheduled charging would be required to support large penetration of EVs without requiring significant upgrades on the existing infrastructure.

To test this hypothesis, the charging start time was shifted 2 hours ahead for different numbers of EVs, to determine the number needed to shift to create a second consumption peak. It was found that a second peak, similar to the nightly residential peak, was obtained when over 70% of the EVs shifted their charging start time (Figure 4.9). Additional simulations are presented in [59].

4.4 Distributed Generation

Active distribution networks offer a promising alternative towards a more sustainable power system, due to their ability to effectively integrate DGs from different energy sources, including renewables. Results

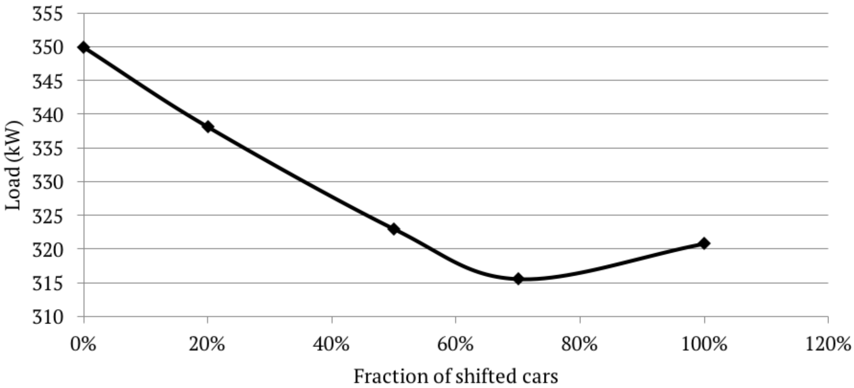

Figure 4.9: Impact of charge scheduling

presented in paper V show not only that the object-oriented mathematical models built in Modelica are valid for simulating DG components, but also that they can be integrated with existing open source libraries (e.g PowerSystems Modelica Library [60]).

Simulation results for the capstone C65 turbine model show that the fuel consumption data matches the measurements obtained from the SCADA system, as shown in Figure 4.10. The x-axis shows each data sample taken every minute and the y-axis represents the gas consumption in m^3/h. A one to two sample delay was found, especially noticeable during ramping up and ramping down of the C65 turbine. In order to reduce this delay, thermal and mechanical inertia parameters should be included in the model and the data acquisition system should be checked for delays between the SCADA and the database, where a timestamp is assigned to each data sample.

Simulation results from the PV model are shown in Figure 4.11. The x-axis shows each data sample taken at every minute and the y-axis represents the power output in kW. The model captures the behaviour of the PV array well, as shown in Figure 4.11 (left), however, results are less accurate during cloudy days, as shown in Figure 4.11 (right), due to the effect of refraction and reflection from passing clouds. In order to improve the performance of the model under these circumstances, the diffused and ground-reflected irradiance parameters should be included in the PV model's equation system.

In paper VI, the climate action plan of the city of Eskilstuna in Sweden was analyzed in order to evaluate the local integration of renewable

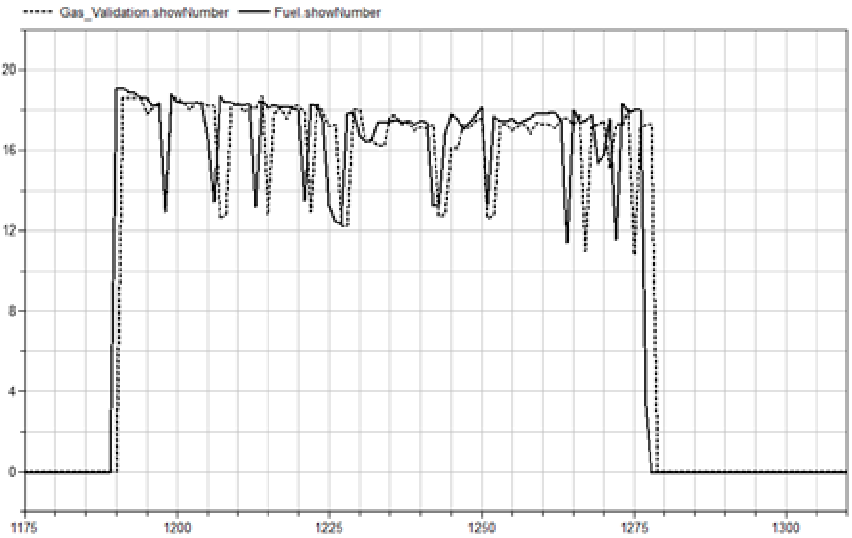

Figure 4.10: Simulated (solid) vs real (dotted) results for a daily profile for the C65 ICHP

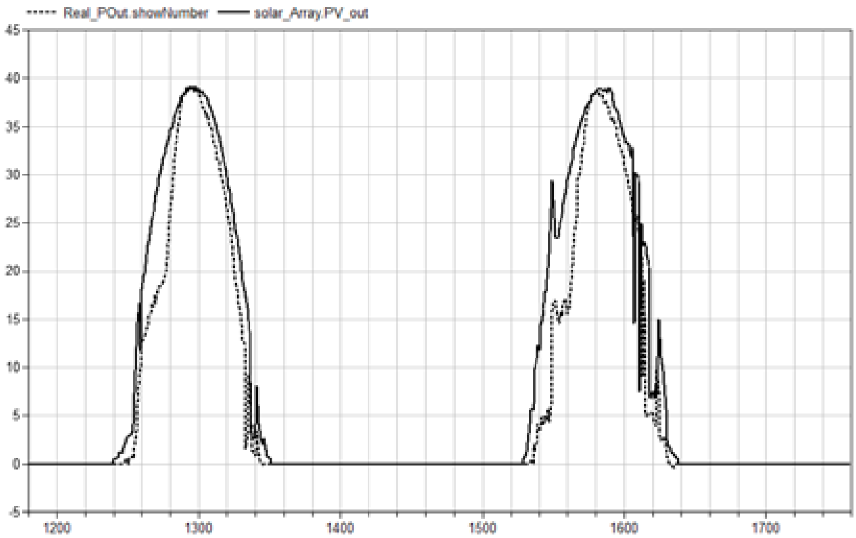

Figure 4.11: Simulated (Solid) vs Real (doted) power (in kW) output from the PV array

energy sources in the municipal area as well as the required infrastructure to support larger penetration of EVs, among other issues. It was found that to reach the expected goals, several adjustments should be carried out. For instance, to achieve the renewable energy goals in the city, a detailed analysis of the most suitable rooftops for installing PV systems should be performed and more funds should be allocated for the required investments. Furthermore, specific information on the distribution network's capacity and self-consumption goals should be defined, to determine the correct size of the PV systems required.

Regarding the CO_2 reduction targets in the transport sector, although large EV penetration is not the top priority, it would contribute significantly to reaching these goals. For this, a larger recharging infrastructure would be required to support the increased adoption of EVs. Additionally, the climate action plan would need to take into account the transportation needs of the city as well as citizens' driving patterns and integrate them with the local production of renewable electricity through an actively controlled distribution network.

Chapter 5

Conclusions

This thesis studied the roles of several actors involved in electric distribution systems through electricity consumption data analysis and simulation models. Several research questions were formulated and addressed through six papers, presented in this work. These research questions are addressed in this section.

What are the main advantages for households from adopting hourly spot market electricity pricing agreements? (Paper I)

A high RTP customer share can enable large adoption of technology-based solutions designed to take advantage of electricity price fluctuations. For example, customers with heat pumps or any other type of electric-based heating system can adopt smart temperature controllers that react to price signals. With such systems, the operation of the heating system can react to price variations in the spot market, and thus optimize operation costs while maintaining adequate indoor conditions. In this study, GSHP users experienced the larger benefits from the use of RTP. Therefore, adopting these technology-based solutions would help increase economic savings even further.

Additionally, mass RTP adoption can enable further adoption of smart grid technologies at the residential level. For instance, deployment of energy storage technologies combined with solar PV systems can increase, due to the associated benefits of storing energy during low-price hours to be used during peak hours. Similarly, RTP can also help boost the adoption of EVs, since users can implement charging control schemes where the vehicle's battery is only charged when the electricity price is low, thereby reducing its mobility-associated costs.

Could households benefit from hourly spot market electricity pricing agreements without adopting DSM strategies? (Paper I)

Most users experienced economic benefits over the 7 year study period when using a RTP contract despite spikes in electricity prices, including the critical fluctuations in the Winter of 2002-2003. These results suggest that customers in Sweden could shift to RTP contracts and still gain economic benefits even without changing their electricity usage patterns (e.g adopting DSM strategies).

What are the main impacts on the energy supply system from adopting different energy conservation measures and increasing DG penetration in residential areas? (Paper II)

The results discussed in the thesis suggest that it is critical to analyze the characteristics of the existing energy supply networks that feed buildings before undertaking large building renovations. This analysis can help city planners decide in which areas different ECMs would have the highest system impact on energy efficiency and greenhouse gases reduction. Moreover, it is important to consider additional measures besides conventional building envelope improvements, such as building automation, distributed generation (e.g. solar thermal, PV, micro CHP etc.), efficient outdoor lighting and energy storage.

What is the electricity demand impact on detached households in Sweden from using ground-sourced heat pumps? (Paper III)

GSHP households can use up to 76.5% more electricity per m^2 than their DH counterparts. This implies that GSHP-based users may be less likely to obtain rapid reductions in electricity use from increased use of energy-efficient appliances and lighting systems, since GSHPs' energy use is heavily influenced by outdoor temperatures, substantially affecting the overall electricity consumption.

However, intensive use of GSHP also increases the possibilities for stimulating automatic demand side management (ADSM) systems, where the temperature settings of the GSHP are controlled based on weather forecasts, network operation and real time electricity price information, in order to provide a more stable demand-supply balance during peak-time conditions. In order to make good use of ADSM systems while maintaining the temperature comfort of the users, the use of energy storage systems should be encouraged, as well as investments in thermal insulation which will increase the effectiveness of ADSM systems. Furthermore, large electricity demand from GSHPs makes it absolutely necessary to use efficient dynamic pricing schemes that would encourage users to make the best use of their GSHPs.

What can be learned from early EV adopters in Sweden to develop strategies that support the penetration of electric vehicles in other countries, and what are the potential impacts on local electric distribution grids from large adoption of EVs? (Paper IV)

The results presented in this thesis characterize the typical EV owner in Sweden as male, with medium-high income, highly educated, living in a 2 or 4 member family in a house usually located in an area with low population density, with daily driving patterns between 30km and 100km, far below the average range of current EVs. Based on the insights provided in this study regarding the location and time of day charging, future business models and information strategies should encourage communication and information exchange between EV owners and electricity suppliers to increase the benefits for the two sectors.

Moreover, in order to achieve a sustainable use of EVs, national and local governments should focus on providing the required charging infrastructure in densely populated areas. However, before deploying this infrastructure, the implications and potential impact on primary and secondary distribution networks should be analyzed.

Furthermore, regarding the EV impact on the distribution network, the results showed that the majority of EV owners charge their vehicles at night. This coincides with the residential evening consumption peak, resulting in voltage violations with EV penetration levels over 30%. Simple load shifting strategies (e.g. 2 hours ahead shifting) created a second consumption peak for the EVs, shifting over 70% of the consumption. Thus, optimal load shifting strategies should be developed in order to prevent overloading the distribution network during evening peak hours. Additionally, since vehicles spend a large amount of time plugged in, and average daily driving distances are far below the vehicle's battery capacity, vehicle owners could benefit from adopting strategies that allow their cars to be part of network controlling agreements (e.g. V2G).

What are the benefits and challenges from using an equation-based, object-oriented modelling language to model DG components in LV distribution networks? (Paper V)

Large adoption of microgrids and active distribution networks offer a promising solution towards a more sustainable power system, mainly thanks to their ability to effectively integrate DGs from different energy sources, including renewables. One of the main challenges for these networks to become more popular is that the conventional distribution system was not designed to include large penetration of DGs, and thus the existing planning, modelling and simulation software packages were also not designed to handle these new networks.

The results demonstrate that as well as the presented modelling approach being valid for simulating DGs, the models can also be successfully integrated with existing open-source libraries. Future work will include developing more components and testing the model's performance with other libraries in order to perform more complex simulations, for instance to combine the operation of the power system with a local district heating network, where both the electrical and thermal performance can be simulated and evaluated under different operation conditions.

What are the best strategies to integrate DG and e-mobility to increase urban sustainability in mid-sized cities in Sweden and its implications on the existing distribution infrastructure? (Paper VI)

To increase renewable energy electricity production in urban areas, prior detailed analysis of the physical capabilities of the city should be performed. For instance, the most suitable rooftops for installing PV systems should be identified and specific information about the distribution network's capacity and self-consumption goals should be established in order to select PV systems with the correct specifications. Regarding the CO_2 reduction targets in the transport sector, larger recharging infrastructure to support increased adoption of EVs would be required. This infrastructure needs to consider the mobility patterns in the city as well as citizens' driving habits in order to integrate them with the local production of renewable electricity through an actively controlled distribution network.

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