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Optimal Operation of EVs and HPs in the Nordic Power System

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To my family.

Summary (English)

The Nordic countries, including Denmark, Finland, Norway and Sweden, have great ambitions in seeking a fully carbon neutral or low-carbon electric power system by 2050. The large scale deployment of electric vehicles (EVs) and heat pumps (HPs) is considered not only as an efficient method to limit the greenhouse gas (GHG) emission and the fossil fuel consumption in the transportation and heating sectors but also as a potential approach to cope with the intermittency due to the further utilization of renewable energy sources (RES) in the Nordic region. With increasing amounts of RES in the power system, more reserves will be needed by the grid due to the inherent uncertainties of RES. EVs and HPs will play a more important role in the future power system of the Nordic region by providing extra flexibility to the grid.

The main objective of the Ph.D. study is to investigate the impacts of the possible large scale deployment of EVs and HPs in the Nordic region on the electrical power system. To facilitate such objective, the study in the Ph.D. project focuses on the following aspects:

- The modeling of the EV and HP demand in the Nordic context.
- The optimal scheduling of EVs and HPs with a high penetration level in the market environment.
- The feasibility investigation of EVs and HPs to provide frequency reserves to the Nordic power system.

To accomplish the researches mentioned above, the driving patterns of the vehicles in the Nordic region and the impacts of the EV and HP demand on the

day-ahead electricity market are also analyzed in the Ph.D. study.

The electrical demand of EVs and HPs under non-market environments is modeled with the detailed driving and heating requirements in the Nordic countries. With the uncontrolled charging scheme, the peak EV charging demand coincides with the peak conventional demand. With the timed charging scheme, the EV charging demand is delayed to avoid the conventional peak demand to some extend. However, most of the charging congregates in a short period when the timed charging is set started. The HP demand with the least-energy-consumption control scheme is consistent with the environmental weather profiles. The increasing HP demand in the evening coincides with the conventional peak hours of the power system which may stress the grid.

A chance constrained programming model through mixed-integer programming (MIP) is proposed to formulate the EV demand in the day-ahead electricity market considering the stochastic characteristics of the EV driving patterns. The model guarantees that the driving requirements of the EVs are met by the day-ahead energy planning with the predefined confidence parameter.

A robust optimization model is proposed to formulate the HP demand in the day-ahead electricity market considering the uncertainty of the weather forecast used in the HP energy planning. The heating requirements for the HPs are guaranteed by the day-ahead energy plans through the robust optimization model.

An aggregative game model is proposed to model the demand of large scale deployment of EVs and HPs in the day-ahead electricity market. The impacts of the EV and HP demand on the electricity spot price are considered in the EV and HP day-ahead energy planning by the proposed model. With a high penetration level, the demand of EVs and HPs shows a "valley-fill" pattern to the grid when it is introduced into the day-ahead electricity market.

A combined modeling of the EV and HP energy planning is proposed for both the energy plans in the day-ahead electricity market and the frequency reserve provision decisions in the ancillary service market. It is shown that both EVs and HPs can provide considerable frequency reserves to the power system along the day in the Nordic region. Vehicle-to-Grid (V2G) technologies which enable the EVs to discharge the batteries in the reserve operations can further utilize the capacity of the EVs and consequently increase the ability of EVs to provide frequency reserves to the power system. Further, the intense weather of the Nordic region in winter does not decrease the ability of EVs and HPs to provide frequency reserves to the power system.

Summary (Danish)

De nordiske lande, herunder Danmark, Finland, Norge og Sverige, har store ambitioner om et fuldt CO_2 neutralt eller kulstoffattigt elnet i 2050. Den storstilede udbredelse af elbiler (electric vehicles, EVer) og varmepumper (heat pumps, HPer) betragtes ikke blot som en effektiv metode til at begrænse drivhusgas (greenhouse gas, GHG) emission og forbrug af fossile brændstoffer i transport- og opvarmningssektorer, men også som en mulig tilgang til at håndtere variationer forårsaget af den udbredte udnyttelse af vedvarende energikilder (renewable energy sources, RES) i Norden. Med stigende mængder af RES i elnettet, vil det være nødvendigt med flere reserver i nettet på grund af de medfølgende usikkerheder i RES. EVer og HPer vil spille en større rolle i fremtidens elnet i Norden ved at give ekstra fleksibilitet til nettet.

Hovedformålet med Ph.d. studiet er at undersøge virkningerne af en storstilet udbredelse af EVer og HPer på elnettet i Norden. For at lette en sådan målsætning, undersøger Ph.d. projektet følgende aspekter:

- Modelleringen af EV og HP efterspørgsel i nordisk sammenhæng.
- Den optimale driftplan for EVer og HPer med en høj penetration i markedet.
- Undersøgelse af udbyttet af at lade EVer og HPer levere frekvensreserver til det nordiske elnet.

For at udføre de undersøgelser, der er nævnt ovenfor, er kørselsmønstre for køretøjer i Norden og virkningerne af EV og HP efterspørgselen på day-ahead elmarkedet også analyseret i Ph.D. studiet.

Elforbruget for EVer og HPer i ikke-markedsmæssige miljøer er modelleret med detaljerede kørsels- og opvarmningsmønstre for de nordiske lande. Med ukontrolleret opladning, falder spidsbelastningen for EV opladning sammen med spidsbelastningen fra det konventionelle elforbrug. Med tidsindstillet opladning, er EV opladningen forsinket for i nogen grad at undgå sammenfald med det maksimale konventionelle forbrug. Men det meste af opladningen hober sig dog sammen i en kort periode, omkring starttidspunktet for den tidsindstillede opladning. HP belastningen for de mindst energikrævende driftsmønstre er betinget af miljø- og vejrforhold. Stigningen i HP efterspørgsel om aftenen falder sammen med den konventionelle spidsbelastning i elnettet, hvilket kan overbelaste nettet.

En chance-begrænset optimerings model der bruger mixed-integer programming (MIP) foreslås til at simulere EV efterspørgsel i day-ahead markedet med hensyntagen til stokastiske egenskaber ved EV kørselsmønstre. Modellen sikrer, at kørselsbehovene i EVer opfyldes af day-ahead planlægningen med en foruddefineret konfidensparameter.

En robust optimerings model foreslås til at modellere HP efterspørgselen i day-ahead elmarkedet med hensyntagen til usikkerhed i de vejrudsigter, der anvendes i driftsplanlægningen for HPer. Kravene til HP opvarmning er opfyldt af day-ahead energiplaner gennem den robuste optimering model.

En aggregative game model foreslås til at modellere efterspørgslen for storstilet udbredelse af EVer og HPer i day-ahead elmarkedet. Virkningerne af EV og HP efterspørgselen på el-spotprisen indregnes i day-ahead planerne for EV og HP med den foreslåede model. Ved høj penetration har efterspørgslen af EV og HP et "valley-fill"mønster, når det er introduceret i day-ahead elmarkedet.

Der foreslås en samlet modellering af EV og HP energiplanlægning for både energiplaner i day-ahead elmarkedet og frekvensreserver i ancillary service markedet. Det påvises, at både EVer og HPer i løbet af dagen kan bidrage med betydelige frekvensreserver til elnettet i Norden. Vehicle-to-Grid (V2G) teknologier, som gør det muligt for EVer at aflade batterierne som reserver kan yderligere udnytte kapaciteten på elbiler og dermed gøre det muligt for EVer at levere frekvensreserver til elnettet. Endvidere betyder det hårde vejr i Norden om vinteren ikke at EVer og HPer leverer mindre frekvensreserver til elnettet.

Preface

This thesis was prepared at DTU Elektro in fulfilment of the requirements for acquiring an Ph.D. in Engineering.

The thesis summarizes the work of the author during his PhD study. It was carried out from October 2012 to September 2015. During this period, the author was hired at Technical University of Denmark (DTU), where he was a Ph.D. student at Center for Electric Power and Energy (CEE).

Lyngby, 30-September-2015

Zhaoxi Liu

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I would like to thank Centre for Electric Power and Energy at Technical University of Denmark, for providing a wonderful working and research environment.

Finally, I am deeply grateful to my family for their love and unwavering support. Most importantly, I would like to thank my very best friend and life companion Jieling Zhong for all her support, encouragement, understanding and tremendous love.

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Acronyms

ASHP	Air Source Heat Pump
BEVs	Battery Electric Vehicles
CHP	Combined Heat and Power Units
COP	Coefficient of Performance
DER	Distributed Energy Resources
DH	District Heating
DSM	Demand-Side Management
EVs	Electric Vehicles
FNR	Frequency-Controlled Normal Operation Reserve
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HPs	Heat Pumps
HTC	Heat Transfer Coefficients
ICE	Internal Combustion Engine
ISO	Independent System Operator
MIP	Mixed-Integer Programming
PEVs	Plug-in Electric Vehicles

POPs	Preferred Operating Points
RES	Renewable Energy Sources
SCOP	Seasonal Coefficient of Performance
SOC	State of Charge
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant

Chapter 1

Introduction

1.1 Background

The Nordic countries, including Denmark, Finland, Norway and Sweden, have great ambitions in seeking for a fully carbon neutral or low-carbon electric power system by 2050 [1]. A number of national plans and projects have been put forwards in order to promote the energy generation from renewable sources and reduce the greenhouse gas (GHG) emission in the Nordic countries [2]. With enough renewable energy sources (RES) in the area, the Nordic region has great potential to achieve the goal. About 65% of the Nordic electricity production in 2011 is from renewable energy and the percentage for CO_2-free energy sources rises up to 85%. It is not only due to the large amount of hydro-power in Norway and Sweden but also due to the growing sources of other renewable energy in the Nordic region [3]. For instance, Denmark has the highest share of wind power around the world at present. It has experienced an increasing wind penetration in recent years and aims at rising the share of wind power in the electricity consumption up to 50% by 2020 [4]. Fig.1.1 shows the wind penetration levels in the leading wind markets around the world in 2014 [5].

The transportation and heating sectors play significant roles in the Nordic energy system. They are the most important consumption besides the industry sector in the Nordic region. With the growing concern on the GHG emission and

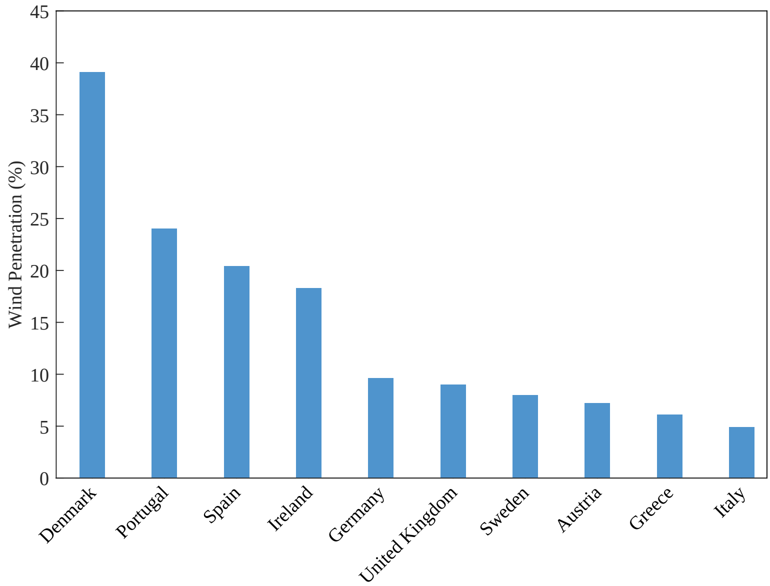


Figure 1.1: Penetration of Wind Power in the Leading Wind Markets of the World in 2014

the fuel security, electric vehicles (EVs) and heat pumps (HPs) are considered as potential alternatives in the daily passenger transportation sector and the space heating sector. Using electricity as the energy source, EVs and HPs can utilize the electricity power which has an increasing proportion of sustainable energy sources in the Nordic region. Meanwhile, they reduce directly the GHG emission in the transportation and heating sectors. Therefore, EVs and HPs have shown promising perspectives in the future.

Furthermore, the large scale deployment of EVs and HPs is considered not only as an efficient method to limit the GHG emission and fossil fuel consumption in the transportation and heating sectors but also as a potential approach to cope with the intermittency due to the further utilization of RES in the Nordic region. With increasing amounts of RES in the power system, more reserves will be needed by the grid due to the inherent uncertainties of RES. Therefore, with the goal of achieving a fully carbon neutral or low-carbon electric power system in the Nordic region by 2050, the demand of EVs and HPs will play a more important role in the future power system of the Nordic region by providing extra flexibility to the grid. Viewed as distributed energy resources (DER), the flexible demand of EVs and HPs is suitable as a frequency reserve source which is necessary for the security operations of the power system. With the ambitious objective of the Nordic region, large scale deployment of EVs and HPs in the

Nordic power system is anticipated.

With large scale deployment of EVs and HPs, the EV and HP demand will inevitably have essential impacts on the grid in regard to different aspects of the power system operations [6]. The impacts from EVs and HPs are closely related to their demand patterns. Therefore, considering the possible high penetration level of EVs and HPs in the future Nordic power system, it is necessary to model the demand of EVs and HPs with the detailed driving and heating requirements in the Nordic context. Furthermore, in order to effectively obtain the flexibility of the EV and HP demand, the investigation on the optimal operations of EVs and HPs not only in the electricity energy market but also in the ancillary service market is a high priority at present.

1.2 Objectives and contributions of the study

1.2.1 Objectives of the study

The main objective of the Ph.D. study is to investigate the impacts of the possible large scale deployment of EVs and HPs in the Nordic region on the electrical power system. The study in the Ph.D. project focuses on the following aspects.

- The modeling of the EV and HP demand in the Nordic context.
- The optimal scheduling of EVs and HPs with a high penetration level in the market environment.
- The feasibility investigation of EVs and HPs to provide frequency reserves to the Nordic power system.

To accomplish the researches mentioned above, the driving patterns of the vehicles in the Nordic region and the impacts of the EV and HP demand on the day-ahead electricity market are also analyzed in the Ph.D. study.

1.2.2 Contributions of the study

The main contributions of this Ph.D. work are as follows:

- Review of the daily duty passenger transportation sector and the space heating sector of Denmark, Finland, Norway and Sweden.
- Review of the status of the EV and HP deployment in the private passenger fleet and the heating sector of Denmark, Finland, Norway and Sweden.
- Driving pattern analysis for EV integration study based on the National Travel Surveys of Denmark, Finland, Norway and Sweden.
- Modeling of the EV demand under non-market environments including uncontrolled EV charging and timed EV charging in Denmark, Finland, Norway and Sweden.
- Modeling of the HP demand under non-market environments with a least-energy consumption control scheme in Denmark, Finland, Norway and Sweden.
- Modeling of the EV demand in the day-ahead electricity market through chance constrained programming to handle the stochastic features of the driving patterns.
- Modeling of the HP demand in the day-ahead electricity market through robust optimization to handle the uncertainty of the weather forecast.
- Modeling of the demand of large scale deployment of EVs and HPs in the day-ahead electricity market with an aggregative game model so that the impacts of the EV and HP demand on the electricity spot price in the day-ahead market can be taken into consideration in the energy planing of the EVs and HPs.
- Combined modeling of the energy planning of EVs and HPs in the day-ahead electricity market and the decisions in the frequency reserve market of the Nordic region.

1.3 Sturcture of the thesis

The rest of the thesis is organized as follows:

Chapter 2: This chapter introduces the transportation and heating sectors of Denmark, Finland, Norway and Sweden respectively. The status of EV and HP deployment in the private passenger fleet and the heating sector of the mentioned Nordic countries is also presented in this chapter.

Chapter 3: This chapter introduces the study on the modeling of the daily driving patterns of the private passenger fleet in the mentioned Nordic countries.

The results of the driving pattern analysis based on the National Travel Surveys of the mentioned Nordic countries are presented in detail in this chapter.

Chapter 4: This chapter introduces the modeling of the electrical demand of EVs and HPs in the mentioned Nordic countries under the non-market environments. The EV charging schemes in the study of this chapter include uncontrolled charging and timed charging. The HP demand is modeled with a least-energy-consumption control scheme.

Chapter 5: This chapter introduces the modeling of the electrical demand of EVs and HPs in the Nordic countries under the market environments. The energy planning of the EVs and HPs in the day-ahead electricity spot market is presented in detail in this chapter. The EV demand is formulated with a chance constrained programming model. The HP demand is formulated with a robust optimization model. In order to take the impacts of the demand of large scale deployment of EVs and HPs on the day-ahead spot price into consideration, an aggregative game model is built and analyzed. The details of the model is also presented in this chapter.

Chapter 6: This chapter introduces the investigation on the capability of the EVs and HPs to provide frequency reserves to the power system in the Nordic region. The modeling of the energy planning of the EVs and HPs in the day-ahead electricity market and the decisions in the frequency reserve market of the Nordic region is presented in detail in this chapter.

Chapter 7: This chapter introduces the conclusions and the scope of the future work of the study.

Chapter 2

Transportation and Heating Sectors in the Nordic Region

Transportation and heating sectors play important roles in the energy system of the Nordic countries. In this section, the daily duty passenger transportation sector and the space heating sector of Denmark, Finland, Norway and Sweden are introduced respectively. The status of the EV and HP deployment in the private passenger fleet and the heating sector of the four mentioned Nordic countries is also presented in this section.

2.1 Transportation Sector in the Nordic Region

Transportation sector is an important sector in the energy system of the Nordic countries. This study focuses on the daily duty passenger transport. The description on the passenger vehicle fleet of the Nordic countries is presented in this section.

2.1.1 Vehicle Fleet in Denmark

The vehicle fleet in Denmark is mainly from private passenger cars. Tab.2.1 shows the stock of the cars, buses and motorbikes in Denmark [7]. As shown in the table, the number of private passenger cars dominates other kinds of vehicles in Denmark. The total number of passenger cars in Denmark increased gradually over the years, a large part of which came from the increase of the private passenger cars.

Table 2.1: Stock of Vehicles in Denmark

	2000	2008	2009	2010
Passenger Cars Total	**1854060**	**2099090**	**2120322**	**2163676**
In Households	1699719	1941978	1965124	1994745
In Business	131510	157112	155198	168931
Taxies	**6059**	**5643**	**5533**	**5316**
Buses Total	**13968**	**14452**	**14509**	**14496**
Coaches	4660	5467	5637	5873
Other Buses	9308	8986	8872	8623
Caravans	**108924**	**140366**	**142354**	**142764**
Motorbikes	**73695**	**143546**	**147373**	**148766**
Moped	**64615**	**61224**	**57866**	**54842**

At present, EVs have a very small share in the passenger fleet of Denmark. Fig.2.1 shows the distribution of the vehicle types in the passenger fleet of Denmark in 2010.

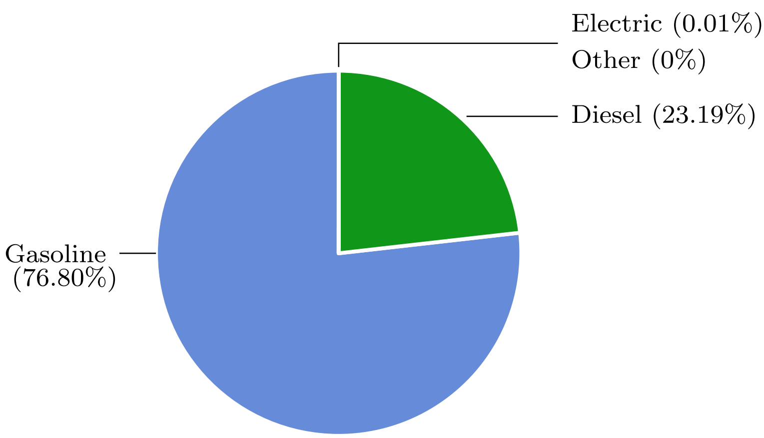


Figure 2.1: Share of Passenger Fleet by Fuel in Denmark in 2010

In 2010, there were about 300 EVs in the passenger fleet of Denmark, accounting for only 0.014% of the total share [7]. However, the market of EVs in Denmark increased rapidly since 2011 and the stock of EVs in Denmark increased to about 3000 by the end of 2014 [8].

2.1.2 Vehicle Fleet in Finland

The majority of the vehicle fleet in Finland are passenger cars. Tab.2.2 shows the stock of automobiles in Finland [9]. As shown in the table, the total number of passenger cars in Finland increased steadily over the years. However, the EV market in Finland is very small at present. There were only about 50 registered EVs in Finland in 2013, 183 in 2014 and this number came to about 360 in 2015 [10].

Table 2.2: Stock of Vehicles in Finland

	2009	2010	2011	2012	2013	2014
Passenger Cars	2776664	2877484	2978729	3057484	3127399	3194950
Vans	332645	347258	365568	379215	391952	404817
Buses, Coaches	13017	13650	14226	14930	15536	16251
Caravans	67526	68909	70230	71262	72092	72786
Motorbikes	216443	226877	236661	244968	251525	257094
Moped	239754	259889	278856	293051	302727	311097

2.1.3 Vehicle Fleet in Norway

The private passenger cars are also the majority of the vehicle fleet in Norway. Tab.2.3 shows registered vehicle numbers in Norway [11]. It is shown that the number of private passenger cars dominates other kinds of vehicles in Norway. It is the most important vehicle in the fleet of Norway.

The number of EVs in Norway is still small compared to the conventional vehicles fueled by petrol or diesel. However, the EV market share in Norway is relatively considerable around world. Fig.2.2 shows the distribution of the vehicle types in the private passenger fleet of Norway in 2014 [12]. EVs had taken up 1.53% of the private passenger cars in Norway by 2014, which resulted from the vigorous growth of the Norwegian EV market in recent years. The number of registered private EVs in Norway increased rapidly from about two thousands in 2010 to about 38.4 thousands in 2014, which represented a growth of nearly 1800% in 5 years [12].

Table 2.3: Stock of Vehicles in Norway

	2008	2009	2010	2011	2012	2013	2014
Private Cars	2197193	2244039	2308548	2376426	2442964	2500265	2555443
Buses	23324	21474	20348	19240	18220	17584	17111
Vans	379343	387546	397279	410730	424634	434636	441967
Lorries	84350	82694	81330	80160	79857	79437	78668
Combined Vehicles	59657	53911	48432	43371	38709	34232	30247
Mopeds	161662	165557	168904	171846	174873	176087	177502
Light Motor Cycles	17677	18475	19089	19775	20614	21349	22115
Heavy Motor Cycles	117044	122760	127503	131875	136212	140474	145534

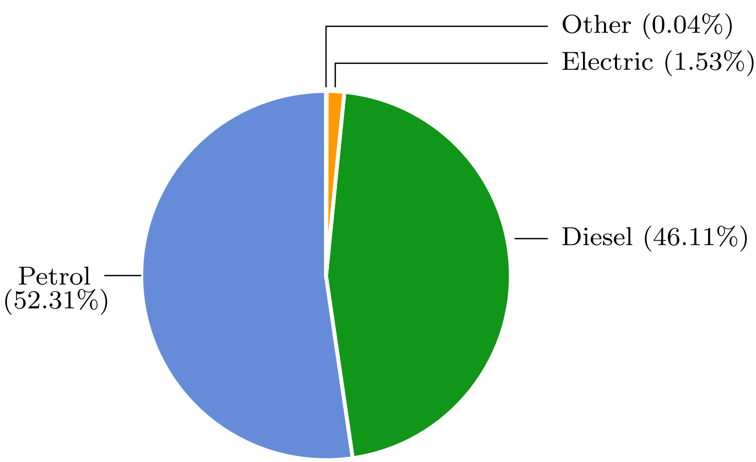


Figure 2.2: Share of Private Passenger Fleet by Fuel in Norway in 2014

2.1.4 Vehicle Fleet in Sweden

Similar to the other Nordic countries, the majority of the vehicle fleet in Sweden are from passenger cars likewise. Tab.2.4 shows the stock of the vehicles in Sweden [13].

Table 2.4: Stock of Vehicles in Sweden

	2008	2009	2010	2011	2012	2013	2014
Pessenger Cars	4278995	4300752	4335182	4401352	4447165	4495473	4585519
Buses	13474	13407	13873	13947	14203	13986	13992
Trucks	510199	514576	526441	548272	556821	565182	581205
Mopeds	1546	1554	3396	2258	2685	3531	3958
Motor Cycles	184422	186987	196158	204428	211195	215043	220314

At present, there are very few EVs in Sweden. EVs only accounted for about 0.05% of the total private passenger cars in Sweden in 2014. However, it should also be noted that the number of EVs in passenger cars in Sweden increased from about two hundreds in 2010 to about 2.2 thousands in 2014 [13].

2.2 Heating Sector in the Nordic Region

2.2.1 Heating Sector in Denmark

Heating sector is amongst the most important energy sectors in Denmark. In year 2010, the observed energy consumption in Denmark was 235TWh with an energy self-sufficiency of 121%, which means the energy production was 21% more than the energy consumption. In the same year, heating took up 64TWh of energy, which was over 27% of the total observed energy consumed in Denmark.

District heating (DH) is well developed in Denmark and supports a considerable proportion of the heating demand to the Danish public. It is now responsible for about half of the net heat demand of Denmark. Further, combined heat and power units (CHP) play an important role in the DH and electrical supply. 77% of DH and 61% of thermal electricity production are supplied by CHP in 2010. According to the data from Danish Energy Agency, throughout Denmark, there are about 16 centralized CHP, 285 decentralized CHP and 130 decentralized HP plants for the public-heat supply; there are about 380 CHP and 100 DH plants for private-heat supply; there are about 500000 wood-burning stoves, 70000 wood-burning boilers, 30000 wood-pellet furnaces and 9000 straw furnaces for individual heat installations [14].

The final heating consumption of Denmark in 2010 was 63702 GWh. Fig.2.3 shows the fuel supply share of the heating in Denmark in 2010 [15]. As shown in the figure, DH took up 48% of the heating demand in Denmark in 2010 while the percentages of renewable waste and natural gas are 21% and 18% respectively. DH, together with renewable waste and natural gas, dominates the heating supply of Denmark in the current stage. Fig.2.4 indicates the trend of the heating consumption by fuel supplies in Denmark from 1991 to 2010 [15].

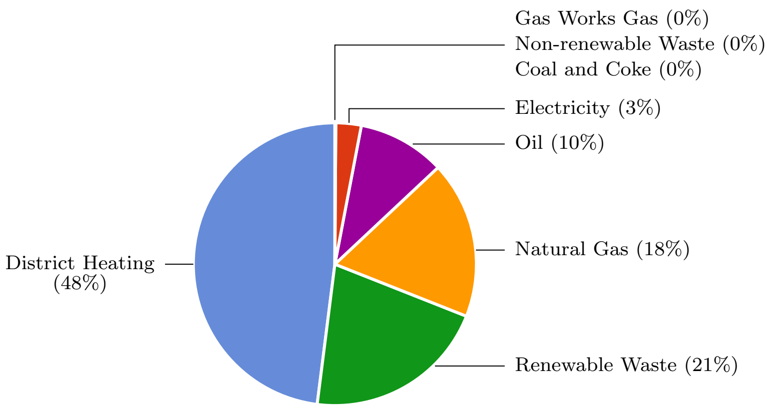


Figure 2.3: Fuel Share of Heating Consumption in Denmark 2010

It is shown that the total consumption for space heating stay rather the same during the years. The fluctuation is mainly due to the climate differences of the years. However, the fuel share of the heating supply changed during the two decades. It is shown that the renewable waste heating supply was on an increase. On the other hand, fossil fuels for heating supply were shrinking generally during the same period, exclusive to natural gas, the consumption of which stayed more or less the same from 1997. Among all the fossil fuels, the decline of oil consumption for space heating is most significant, for over 65% in 20 years. Up to year 2010, the heating demand in Denmark supplied by fossil fuels including oil, natural gas, coal and coke amounted to 17603GWh/year, taking up about 28% of the total space heating energy consumption.

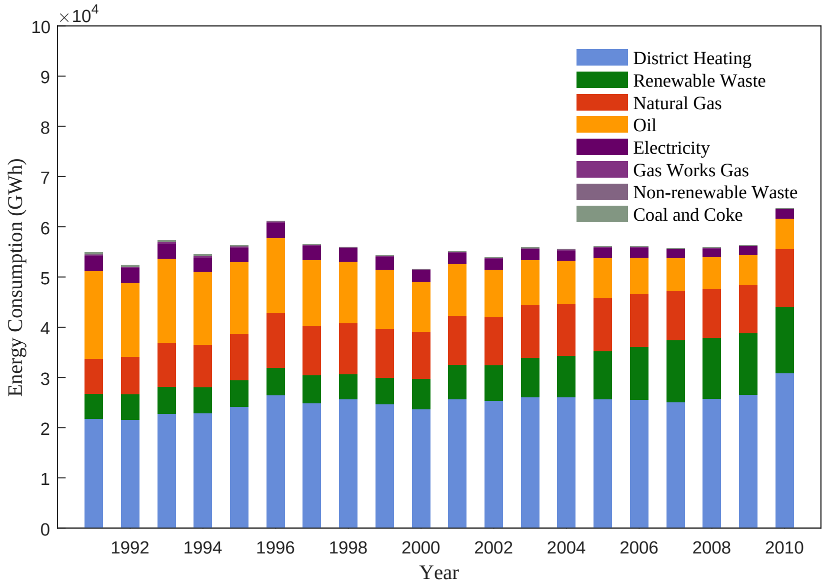


Figure 2.4: Trend of Heating Supply from 1991 to 2010 in Denmark

2.2.2 Heating Sector in Finland

Heating is the largest energy consumption sector besides industry in Finland. The total energy consumption for space heating in Finland was about 83TWh in 2010. It accounted for 26% of the final energy consumption in Finland as shown in Fig.2.5 [16].

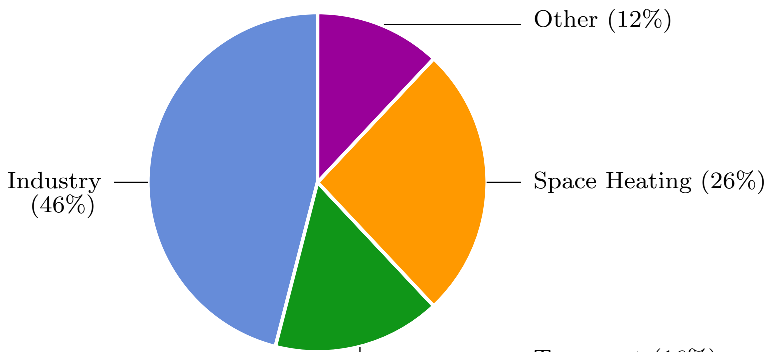


Figure 2.5: Final Energy Consumption by Sectors in Finland in 2010

The heating of Finland is mainly supplied by DH and electric heating. Fig.2.6 shows the fuel supply share of Finnish space heating in 2010 [17]. DH is the most important heating supply in Finland with nearly half of the total space heating market share. Electric heating including direct electric heating and HPs, accounting for 28.4% of total energy consumption, is the second largest heating supply in Finland.

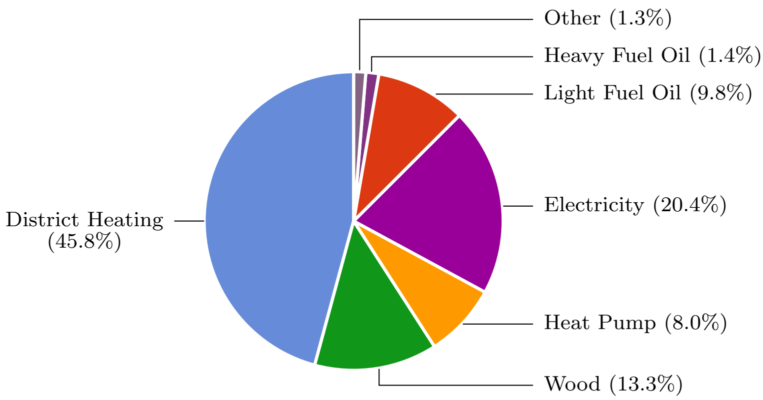


Figure 2.6: Fuel Supply Share of Space Heating in Finland in 2010

2.2.3 Heating Sector in Norway

Heating sector is an important sector in Norway. The need for building heating accounts for about 45TWh per year in Norway [18]. It is about one fifth of the total energy consumption in Norway. The major heating supply in Norway is in the form of electric heating. Electricity dominates the energy sources for the heating in Norwegian households. It is the main heating source due to the fact that the price of electricity in Norway has been considered amongst the lowest in Europe for a long period although it has been increasing and has approached a Europe average [2]. Tab.2.5 shows the percentages of households with different types of heating equipments in Norway. As shown in the table, over 90% of the households in Norway use direct electric heating. However, 80% of households also have other heating technology, mainly wood fueled [19]. The market share of DH in the heating sector of Norway is relatively low among the Nordic area, with a total consumption of only 4.3TWh in year 2010 [20]. Meanwhile, it is worth noting that the number of the households having HPs as their main heating source increases in Norway during the recent years as a result of the increasing electricity price.

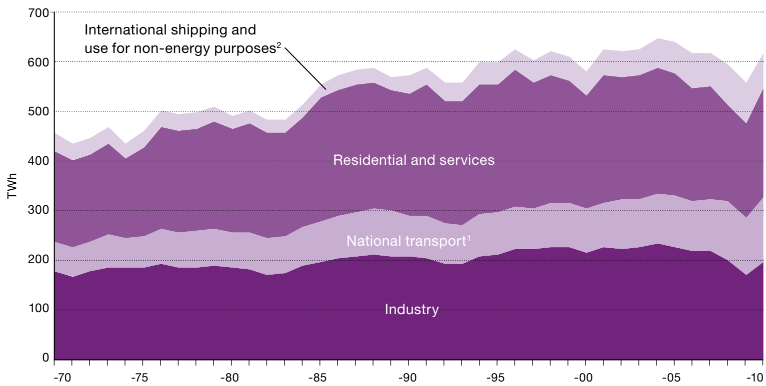
Table 2.5: Households with Different Kinds of Heating Equipment in Norway in 2009

Heating Equipment (%)	Total	Farm-houses	Detached Houses	Terraced etc.	Block
Electric Space Heaters or Electric Floor Heating	94.8	93	97	93	92
Stove for Oil / Kerosene	5.0	4	7	7	0
Stove for Solid Fuels / Open Fire Place	67.3	96	88	64	26
Stove for Pellets	0.7	0	1	1	0
Open Fire Place	9.5	14	14	6	4
Closed Stove for Fuel Wood	64.6	94	84	62	24
Combined Stove for Fuel Wood and Oil	10.5	19	12	14	3
Stove for Oil / Kerosene and/or Combined Stove for Fuel Wood and Oil *	13.7	20	16	19	3
Stove for Solid Fuels / Open Fire Place and/or Combined Stove for Fuel Wood and Oil *	71.9	100	92	73	27
Open Fire Place + Other Heating Equipment, but Not Closed Stove for Fuel Wood	2.7	2	4	2	2
Common or Individual Central Heating Total, excl. District Heating	8.0	8	6	4	15
Common Cetral Heating, excl. District Heating	4.2	0	0	2	15
Individual Central Heating	3.9	8	6	2	0
District Heating	2.0	0	0	2	6
Heat Pump Total	18.5	17	33	8	2
Ambient - Air Heat Pump	16.8	12	31	8	1
Geothermal or Ground - Source Heat Pump	1.8	4	2	1	1
Heat Recovery	7.3	3	8	9	7
Gas Stove	2.5	0	3	3	3

* Some households have combined stove for oil and wood in addition to stove for only fuel wood or oil. These are added up here in order to better illustrate the share of households who in reality can use oil or fuel wood.

2.2.4 Heating Sector in Sweden

Fig.2.7 shows the total energy use in Sweden from 1970 to 2010. Sweden's total energy use stayed on a plateau around 600TWh since 1995. Variations between individual years may be due to fluctuations in the economy and cold winters. Total energy use in 2010 amounted to 616TWh: of this, the total final energy use in industry, transport and residential sector amounted to 411TWh. The remainder, 205TWh, consisted of losses, the use of fuel oils for overseas transport, and use for non-energy purposes. In 2010, energy use in the residential and sector was 166TWh, representing 40% of the total final energy use. Almost 60% of the sector's energy use is for heating and hot water, which is one of the most important energy demand in Sweden [21].



Source: Swedish Energy Agency and Statistics Sweden.
Note: 1. International avation are included until year 1989.
2. International aviation are included since 1990.

Figure 2.7: Total Energy Use in Sweden

In 2010, a total of about 85TWh was used for heating and hot water in residential and non-residential premises. 42% of this were used in house building, 31.5% in multi-dwelling buildings and 26.5% in offices, shops and public buildings as shown in Tab.2.6 [22].

For house buildings, electricity is the most common form of energy used for heating and hot water, 16TWh were used in 2010. The greatest increase in recent years was in biofuels, including firewood, wood chips, sawdust and pellet. In 2010, the use of biofuels in this sector was over 12TWh while the DH use was less than 6TWh. The oil use declined steadily from 9TWh in 2002 to 1.3TWh in 2010. DH is the most dominant form of energy used for heating and hot water in multi-dwelling buildings as well as non-residential premises. In 2010, the use of DH was 24.9TWh in multi-dwelling buildings and 18.5TWh in non-

Table 2.6: Energy Consumption for Heating and Hot Water According to Energy and Building Type in Sweden

Energy Consumption (TWh)	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total	**89.2**	**90.1**	**88.9**	**85.3**	**80.9**	**78.2**	**75.3**	**79.1**	**84.9**
Houses	38.6	38.4	37.9	36.0	34.1	31.8	31.9	34.7	35.8
Multi-dwelling Buildings	27.9	28.5	27.4	26.8	25.5	25.2	24.0	23.9	26.7
Non-residential Premises	22.6	23.2	23.6	22.5	21.3	21.2	19.4	20.4	22.4
Oil	**14.8**	**13.7**	**12.6**	**8.6**	**6.1**	**4.7**	**3.3**	**2.8**	**2.5**
Houses	9.0	8.1	7.8	5.4	3.4	2.6	2.0	1.5	1.3
Multi-dwelling Buildings	2.5	2.4	1.9	1.3	1.1	0.7	0.5	0.4	0.4
Non-residential Premises	3.3	3.2	2.9	1.9	1.6	1.4	0.8	0.9	0.9
District Heating	**41.0**	**42.1**	**41.9**	**42.4**	**41.8**	**42.4**	**42.5**	**43.4**	**49.2**
Houses	3.0	3.6	3.7	3.7	4.7	4.2	5.4	5.2	5.8
Multi-dwelling Buildings	23.3	23.3	22.8	23.1	22.4	22.8	22.3	21.9	24.9
Non-residential Premises	14.7	15.2	15.5	15.5	14.7	15.4	14.8	16.3	18.5
Electric	**21.8**	**21.8**	**22.6**	**20.6**	**20.7**	**18.2**	**16.6**	**18.0**	**19.4**
Houses	16.5	15.8	16.3	15.3	15.3	13.7	12.9	14.6	16.1
Multi-dwelling Buildings	1.5	2.1	2.1	1.7	1.5	1.2	0.8	1.1	1.0
Non-residential Premises	3.8	3.9	4.2	3.6	3.9	3.3	2.9	2.2	2.2
Firewood, Wood Chips, Saw Dust, Pellets	**10.4**	**11.4**	**10.9**	**12.0**	**11.1**	**11.9**	**12.1**	**13.9**	**13.0**
Houses	9.9	10.7	10.0	11.2	10.4	11.1	11.4	13.0	12.4
Multi-dwelling Buildings	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Non-residential Premises	0.3	0.4	0.6	0.3	0.5	0.6	0.5	0.6	0.5
Gas	**1.2**	**1.2**	**0.9**	**1.4**	**1.0**	**0.9**	**0.7**	**0.8**	**0.7**
Houses	0.3	0.2	0.2	0.4	0.3	0.2	0.2	0.2	0.2
Multi-dwelling Buildings	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.2	0.2
Non-residential Premises	0.5	0.5	0.4	0.6	0.4	0.4	0.3	0.4	0.3
Other	**-**	**-**	**-**	**0.4**	**0.2**	**0.1**	**0.1**	**0.2**	**0.1**
Houses	-	-	-	-	-	-	-	0.1	0.1
Multi-dwelling Buildings	-	-	-	-	0.0	0.0	0.0	0.0	0.0
Non-residential Premises	-	-	-	0.4	0.2	0.1	0.1	0.1	0.0

residential premises, taking up 93.3% and 82.6% of the total energy use in the corresponding sectors.

As is indicated in Tab.2.6, DH, electric heating and biofuels are the most important heating supplies in Sweden. The non-sustainable fuels for heating were shrinking over the years. In 2010, the total energy for heating residential and non-residential premises from oil, gas and other heating sources was only 3.3TWh.

2.2.5 Heat Pumps in the Nordic Region

HPs have been experienced a rapid increase in the heating sector in the Nordic region.

Along with the growing importance of HPs in Danish energy policy, the stock of HPs in Denmark is accelerating in recent years. By 2010 there were about 40,000 HPs installed in Denmark, which are with different types including the air source ones or the ground source ones [23]. A survey focusing on the ground-to-water and air-to-water HPs was carried out by COWI for the Danish Energy Agency [24]. Tab.2.7 from this survey shows the numbers of installations, average seasonal coefficient of performance (SCOP), heat produced, electricity consumed and load for all ground-to-water and air-to-water HPs used for heating in permanent housing in Denmark in 2011.

It is shown from the table that the central and southern region of Denmark has the most ground-to-water and air-to-water HPs. On the other hand, the capital region has the least share, which may result from the domination of DH in the heating market of this area. The average SCOP is 2.98 and the total heat production is around 400GWh with an electricity consumption of 134GWh per year. The average SCOP is over the EU efficiency criterion that SCOP should be over 2.63. This number will possibly keep rising along with proper installations of new HPs with higher efficiency.

The growth speed of HP market in Finland is also very fast in recent years. Tab.2.8 shows the penetration of HPs in Finland [25]. The total capacity of HPs in Finland rose dramatically from 164MW to 1362MW between year 1997 and 2009. Further, the heat generated per year rose from 611GWh in 1997 to 2664GWh in 2009.

Due to the increasing electricity price, the HP market in Norway is on a rapid increase in recent years to replace the conventional direct electric heating. In 2012, 27% of all households had a HP in Norway, which is nearly a 9-percent-

Table 2.7: Total Number of Ground-to-Water and Air-to-Water HPs in Denmark in 2011

Geographical Region and House Type	Number	Average SCOP	Heat Production (MWh)	Electricity Consumption (MWh)	Network Load (kW)
Capital Region	**3919**	**2.85**	**54516**	**19141**	**8666**
Single-family Houses	3023	2.86	41771	14565	6623
Terrace Houses	473	2.59	4946	1911	959
Farm Houses	424	2.95	7859	2664	1085
Central Denmark Region	**7505**	**3.02**	**107669**	**35662**	**16821**
Single-family Houses	5085	2.97	68978	23222	11175
Terrace Houses	177	2.54	1905	750	371
Farm Houses	2242	3.15	36786	11690	5276
North Denmark Region	**4393**	**3.09**	**67289**	**21753**	**10271**
Single-family Houses	2871	3.08	42236	13723	6610
Terrace Houses	60	2.46	697	283	136
Farm Houses	1462	3.14	24356	7746	3525
Zealand Region	**4568**	**2.85**	**65951**	**23123**	**10505**
Single-family Houses	3441	2.80	47814	17088	7759
Terrace Houses	210	2.67	2	798	410
Farm Houses	917	3.06	16009	5237	2336
South Denmark Region	**6967**	**3.01**	**104205**	**34649**	**15760**
Single-family Houses	5030	2.95	69437	23540	11066
Terrace Houses	147	2.74	2168	790	341
Farm Houses	1790	3.16	32600	10319	4353
Total	**27352**	**2.98**	**399630**	**134327**	**62024**

Table 2.8: Penetration of HPs in Finnish Heating Market

Year	Air Source Heat Pumps			Ground Source Heat Pumps		
	Amount	Heat Capacity (MW)	Generated Heat (GWh)	Amount	Heat Capacity (MW)	Generated Heat (GWh)
1997	4427	17	26	15592	147	585
1998	5228	20	30	16324	153	612
1999	5725	22	31	17264	162	621
2000	6525	26	32	16835	158	536
2001	7566	31	41	16376	154	601
2002	9696	41	51	15708	148	584
2003	15560	67	80	15696	148	581
2004	24710	109	124	16953	159	608
2005	43170	194	211	20073	189	691
2006	75272	348	380	24551	231	849
2007	104818	489	535	29698	279	1004
2008	156721	750	851	37336	351	1202
2009	198235	958	1132	42996	404	1532

* Air source heat pumps include air-air, air-water and exhaust air heat pumps.

point increase than the case in 2009 and this share was only 8% in2006. In particular, it is households in detached houses and farmhouses that invest in a HP [26, 27]. Approximately 15000 ground source heat pumps (GSHPs) were estimated to be operating in Norway in 2007. In 2008 air-to-water HPs appeared to make a significant breakthrough into the market, judged by the continued increase in applications for government grants. Most HPs in Norway installed in houses are air-to-air, and the residential sector is the main market for these. They are dominant because water-based central heating is relatively rare and air-to-air HPs are easier and less expensive to install than GSHPs. In the commercial and public sectors of Norway, 50% of the energy used for heating is provided via central heating. 3% of the buildings with central heating systems have HPs [28].

The Swedish HP market has been up and down since 1980's [29]. However, in recent years, the installation of HPs in Sweden is on a continous increase. In 2010, the number of HPs in dwellings and non-residential premises was estimated to be 841000. The majority of these, 805000 HPs or 95%, can be found in one-dwelling and two-dwelling buildings. Geothermal and lake water HPs were the most common types of HPs installed in Sweden [22].

2.3 Summary

The transportation and heating sectors play significant roles in the energy system of the Nordic region. The private passenger transportation and the space heating are both important energy consumptions of the Nordic countries. At present, the market share of EVs and HPs in the Nordic countries is still at a fairly low level. Regarding the private passenger transportation, most of the vehicle fleet in the Nordic countries are conventional internal combustion engine (ICE) vehicles which are mainly fueled by petrol or diesel. The EV integration in the sector can reduce both the fossil fuel consumption and the GHG emission. For the space heating in the Nordic region, the energy share of non-renewable sources is decreasing in recent years. However, there is still a non-ignorable proportion of these sources. The deployment of HPs can reduce both the fossil fuel consumption and the GHG emission for space heating. Further, there is a considerable share of direct electric heating in Finland, Norway and Sweden, especially in Norway. The replacement of direct electric heating by HPs can reduce the energy consumption of heating due to the fact that the coefficient of performance (COP) of a HP is always over 1 in normal operations. Currently, both of the EV and HP markets have been experiencing a rapid increase in the Nordic region. It shows extensive market prospects in the private passenger transportation sector and the space heating sector for EVs and HPs in the Nordic region.

Chapter 3

Driving Pattern Analysis for EV Integration Study in the Nordic Region

This chapter presents the driving pattern analysis in the Nordic countries including Denmark, Finland, Norway and Sweden. The driving data are obtained from the national travel surveys of the mentioned Nordic countries. The key parameters of daily driving patterns for EV integration study including the driving distance and the charging availability are studied.

3.1 Daily Driving Patterns in the Nordic Region

Driven by different motivations, many studies focusing on different aspects of the vehicle driving patterns have been carried out. For example, the work in [30–32] studied the speed and acceleration profiles to estimate the emission and fuel use of vehicles. The work in [33] carried out the driving pattern prediction on a specific driving course for the energy management of vehicles. The work in [34] studied the driving data in China to develop the driving cycle for the purpose of vehicle emissions and energy consumption estimation and traffic impact assessment. [35] used the GPS based data to develop a duty cycle for the plug-in vehicles in the North American urban setting. The work in [36] used GPS based information collected over one month from 360 vehicles to assess the feasibility of EVs in Copenhagen. [37] analyzed the daily driving requirements of vehicle drivers with GPS-based driving information collected from 484 vehicles in Atlanta of the United States. [38] used the real-world driving data that comprise 4409 trips in Southeast Michigan of the United States to build a model of the daily driving mission for studies of real-world PHEV usage. [39] developed a driving pattern recognition method for EV range estimation. [40] used the travel data from the Transportation Tomorrow Survey in Toronto to study the impacts of driving patterns on tank-to-wheel energy use of PHEVs. [41] studied the driving data in Australia from GPS devices to access the feasibility of battery electric vehicles (BEVs). [42] analyzed the data of 11 EVs and 23 charging stations from the Western Australia Electric Vehicle Trial in order to obtain the features of the EV charging events. [43] analyzed the daily and yearly driving pattern in France to compare the competitiveness of electric driving with different power train technologies.

The daily driving patterns of the vehicles are essential to the studies of EV integrations to the power system. Most of the driving pattern studies at present serve for the purposes of emission and energy consumption assessment of conventional vehicles, driving energy management, feasibility evaluation and driving range estimation of EVs. Generally, they focus on single driving cycle analysis, driving status recognition or daily driving distance range quantification. However, the EV integration study to the power system has its own concern for different aspects of the vehicle driving patterns. For example, the time series of the driving distance and the driving/parking status of the vehicles along the day are essential to enable the detailed EV integration researches such as EV day-ahead charging energy planning, EV coordinated scheduling investigation, etc. Besides, many driving pattern studies currently are based on the GPS data which are collected from limited number of vehicles in confined area. As the power system analysis usually covers a larger scope, it will improve the accuracy of the EV integration study if the driving patterns are studied with the data from a more comprehensive sample space. At present, a thorough study on the detailed driving patterns for the EV integration studies in the Nordic region is missing.

3.2 National Travel Surveys of the Nordic Countries

In the driving pattern analysis for the EV integration studies, it is important to obtain the driving behaviors of EVs. Currently, it is difficult to obtain statistically significant data of the daily driving behaviors of EVs directly. Due to the limitation of the current EV driving range and refueling support compared to the conventional internal combustion engine vehicles, the drivers with moderate driving requirements are more likely to use EVs at present and there are very few EVs for daily driving on the road. Therefore, the sample space is relatively limited and the driving pattern is not general. However, with a large scale deployment of EVs and sufficient support of charging facilities, the driving pattern of EVs shall be more or less same as the conventional passenger cars since all the daily driving requirements should be fulfilled. Therefore, it is feasible to use the driving pattern of conventional passenger cars in the Nordic area to estimate the driving pattern of EVs. The National Travel Surveys of the four mentioned Nordic countries are the most comprehensive data sources which have enough samples to represent the travel behaviors statistically in the corresponding Nordic region. Detailed information of the drivers as well as the driving behavior records in one particular day is contained in the National Travel Survey datasets.

The datasets from the National Travel Surveys provide the driving behaviors of survey respondents. The information of vehicles with details of the driving behavior of other driving license holders (if there are any) in the household of the respondents is not available. Such feature of the National survey datasets may lead to inaccurate outcomes if the datasets are used directly in the EV driving pattern analysis since the driving behaviors can be different between the individual respondents and the individual vehicles. The driving requirement would be underrated, and the EV charging and discharging availability may be overestimated. For instance, in case of one car and two household members with driving licenses in the household, the car could drive twice distance as the result of using the data directly.

In order to deal with the issue discussed above, a statistical process was used to transform the daily driving behavior observations of individual respondents to the behavior of individual vehicles. The steps of the process are illustrated in the flowchart shown in Fig.3.1.

The datasets of the National Travel Surveys were divided into four categories according to the numbers of the driving license holders and the cars in the household of the respondents and processed differently. The four categories of

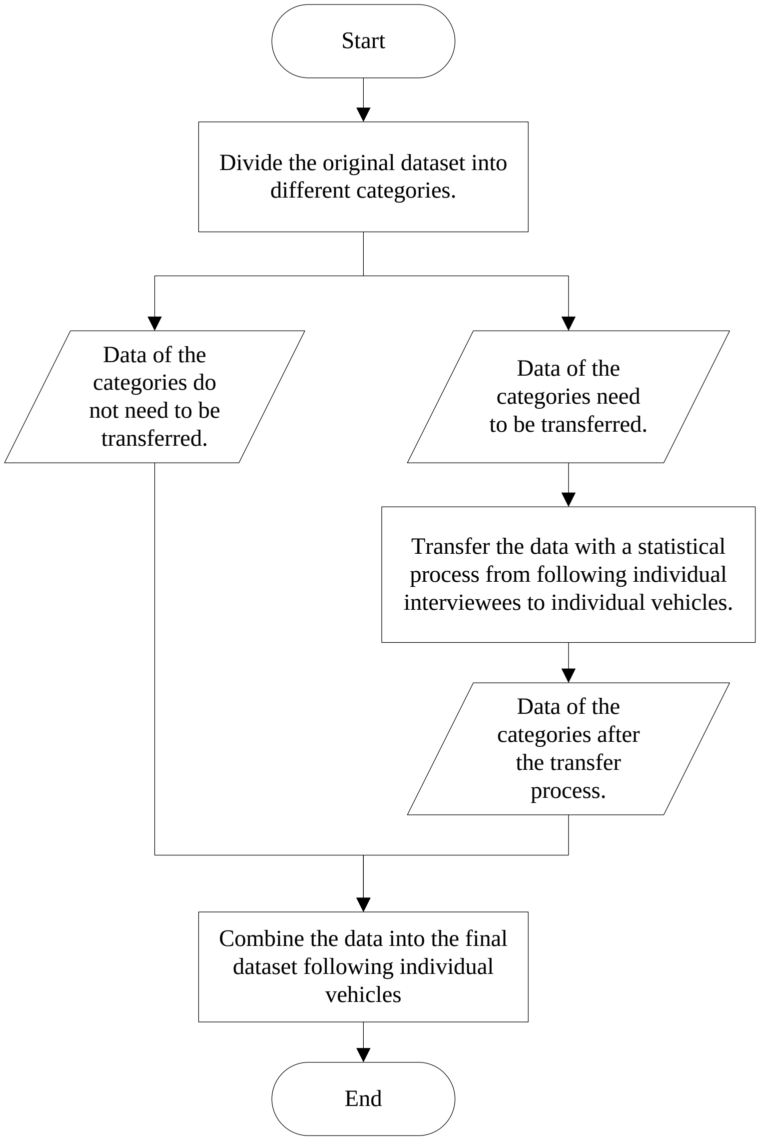


Figure 3.1: Main Steps of Transferring the Dataset from Following Individual Interviewees to Individual Vehicles

the dataset are listed as follows:

- Category 1 - the car number equals to the number of the driving license holders in the household of the respondent.
- Category 2 - there are one car and two driving license holders in the household of the respondent.
- Category 3 - there are one car and three driving license holders in the household of the respondent.
- Category 4 - others.

For Category 1, the driving behaviors of the respondents are considered as same as the driving behaviors of one car in the household. Such assumption is statistically reasonable if each driver only drives his/her own car or the driving behaviors distribute equally among all the cars in the household. Bias on the driving patterns is introduced with such assumption under certain situations. For example, the cars in the household may be functionally divided such as daily commuting and leisure driving for all the drivers in some cases when there is more than one car in the household. However, the size of the bias is small and is assumed to have a small effect on the results of the study.

For Category 2, the driving behaviors of the car cannot be assumed to be the same as the driving behaviors of the respondent. A transformation process is introduced in this case. With the assumption that similar drivers have similar driving patterns statistically, the other respondents in the dataset with the same characteristics as the other driver in the household of the main respondent is selected under a statistical process to imitate the main respondent's driving companion for sharing the car.

The driving behaviors of the imitative companion and the main respondent are combined to constitute the driving behaviors of the car. The imitative driving companions and the other driver in the household of the main respondent should have the same characteristics such as gender, age (difference within 5 years), the same recorded day of the week (weekdays, saturday or sunday), etc. Their driving activities are checked with the driving activities of the main respondent. There shall not be any overlap during the driving periods of the two drivers throughout the day. A further but reasonable assumption is that the car can only be exchanged at home.

For Category 3, a similar transformation process is done as the second category. However, there is an extra matching process for the imitation of the second driving companion of the main respondent.

The first three categories mentioned above make up the majority of the whole datasets of the National Travel Surveys. By combining the second and third categories after the transformation processes with the first category, the datasets of the detailed driving records following individual vehicles are created. The other observations outside all the three categories are less than 6% of the whole datasets and left out of the analysis.

3.3 Driving Distance

The driving distance is one of the most important parameters of the driving requirement which needs to be fulfilled in the EV integration study. Consequently, it will affect the charging requirement and the discharging operation possibility of the EVs.

The data in the National Travel Surveys contain the starting time, the end time and the driving distance of all the trips in a day. The cumulative driving distance can therefore be calculated accordingly. At the end of one trip, the driving distance of the trip is cumulated. By following the records of all the trips in the day, the cumulative driving distance of the vehicle along the day is obtained. Fig.3.2 shows an example of the cumulative driving distance of a car along the day.

In the Nordic area, the daily driving distance of the vehicles is not very high. The average daily driving distances of the Nordic region are listed in Tab.3.1. The results of the driving distance analysis are consistent with the average driving distance data of vehicles from the statistical data of the four mentioned Nordic countries.

Table 3.1: Average Daily Driving Distance in the Nordic Region

Country	All-Days (km)	Weekdays (km)	Weekends (km)
Denmark	40.0	43.4	32.0
Finland	46.8	45.2	51.0
Norway	35.6	36.6	33.2
Sweden	32.0	35.2	30.6

All the four Nordic countries have an overall average driving distance less than

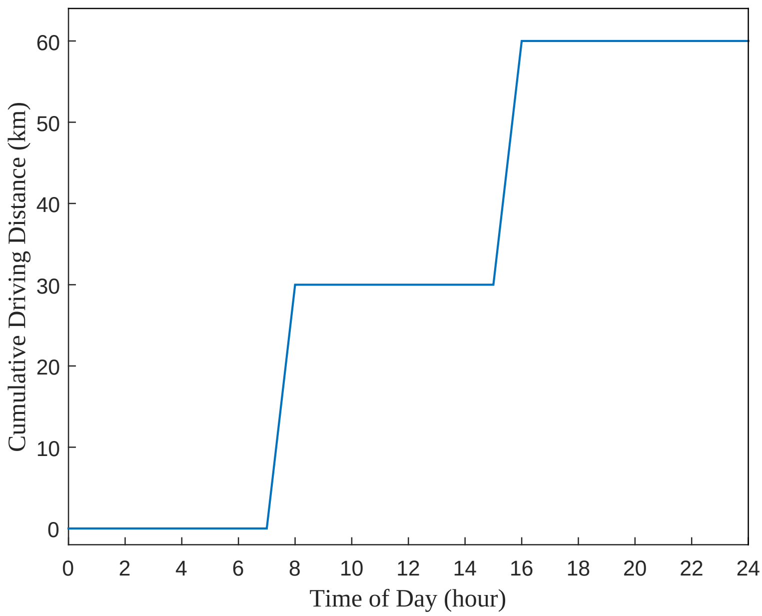


Figure 3.2: Cumulative Driving Distance of a Vehicle along the Day

50 km per day, which is not a very long distance and can be supported by the current EV technologies. Specifically, Sweden has the shortest average driving distance among the four countries while Finland has the highest number. In Denmark, Norway and Sweden, the average daily driving distance on weekdays is longer than that on weekends. However, it is in the opposite way in Finland. It shows a relatively long driving distance with 51 km in Finland on weekends. This is mainly due to the more active driving behaviors and longer driving distance for the trips to the second homes, the culture event, sports event, entertainment, restaurants and social evenings on weekends in Finland.

Fig.3.3 and Fig.3.4 shows the cumulative driving distance of the vehicles on weekdays and weekends, respectively. The curves of the cumulative driving distance of the four counties have similar trends on weekdays. The driving distances start to accumulate in the morning and have a rapid increase in the evening. Eventually, they reach the final plateau at around 24 pm at the end of the day. On the other hand, the cumulative driving distances in Denmark, Norway and Sweden form the curves with more gentle slopes on weekends. The distance in Finland increases steadily and rapidly from the morning to the evening and results in the relatively long driving distance on weekends.

In the Nordic region, the daily driving distances of most of the vehicles are in

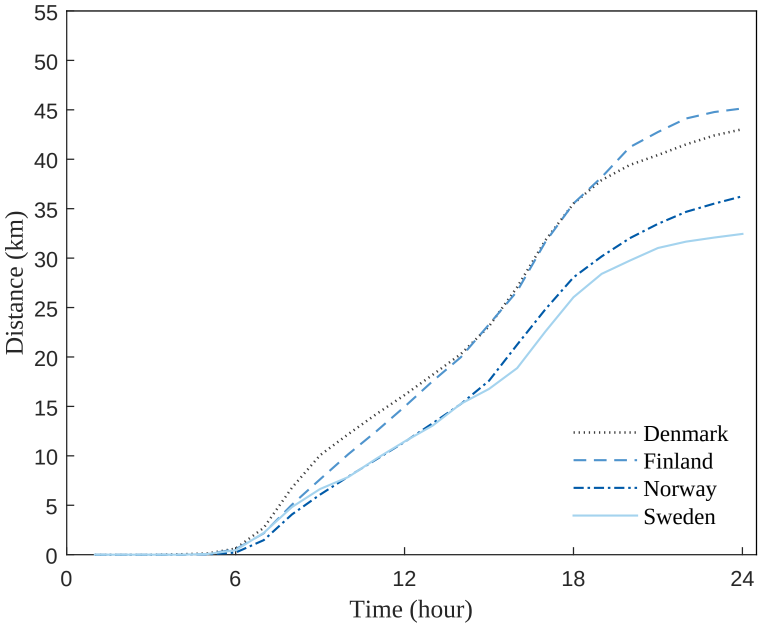


Figure 3.3: Cumulative Driving Distance in the Nordic Region on Weekdays

the short distance range. Such everyday driving distance distribution provides a high possibility for the EV integration. The daily driving distance distributions of the Nordic region are as shown in Fig.3.5. The detailed numbers of the cumulative driving distance in the Nordic region on weekdays are shown in Appendix A.1. About 64% of the vehicles in Denmark and 65% of the vehicles in Finland have a driving distance less than 40 km per day on weekdays. The percentages in Norway and Sweden are about 73% and 74%, respectively.

Such a feature is more obvious on weekends. Fig.3.6 shows the daily driving distance distributions of the Nordic region on weekends. The detailed numbers of the cumulative driving distance in the Nordic region on weekends are shown in Appendix A.2. Over 75%, 77% and 78% of the vehicles in Denmark, Norway and Sweden have a daily driving distance less than 40km on weekends, respectively. The percentage for Finland is about 66%, showing more active driving behaviors in Finland on weekends.

It is shown that people drive more on weekdays than on weekends in Denmark as the vehicles are mainly for the daily commuting purpose between home and the workplace. The driving activities are more active in Finland than the other three countries, especially on weekends. Norway and Sweden show moderate

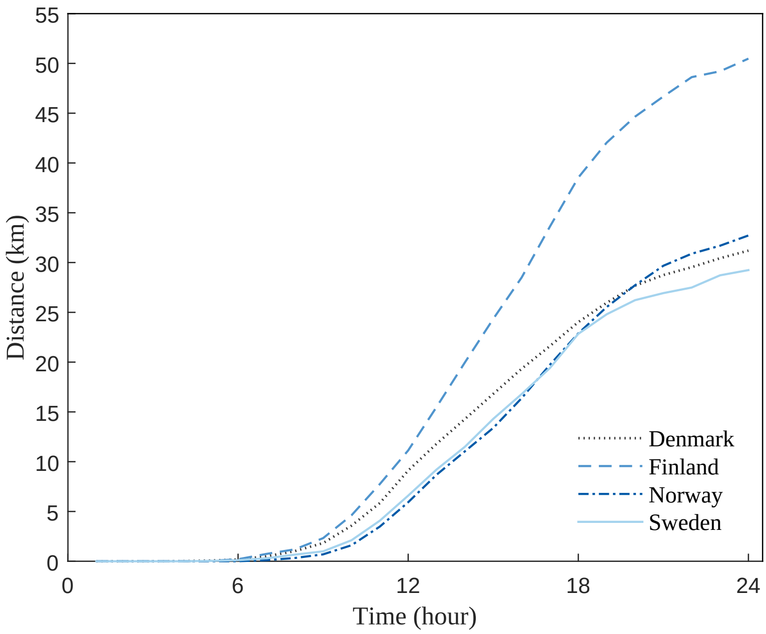


Figure 3.4: Cumulative Driving Distance in the Nordic Region on Weekends

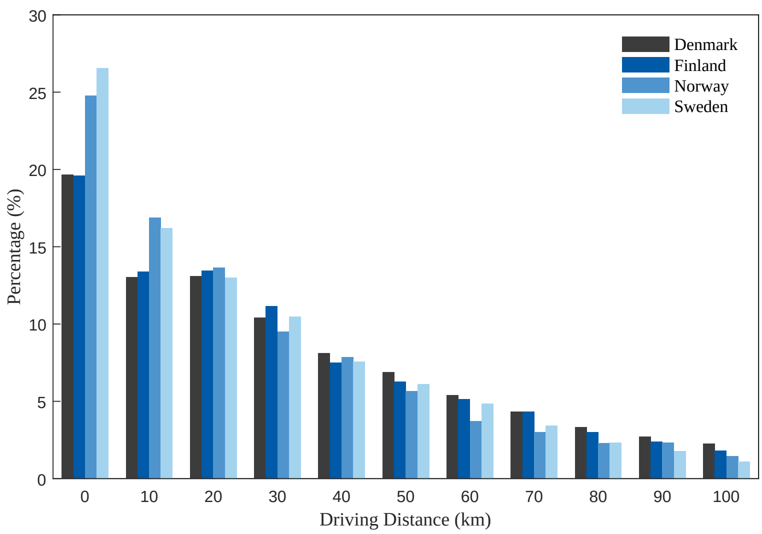


Figure 3.5: Daily Driving Distance Distribution in the Nordic Region on Weekdays

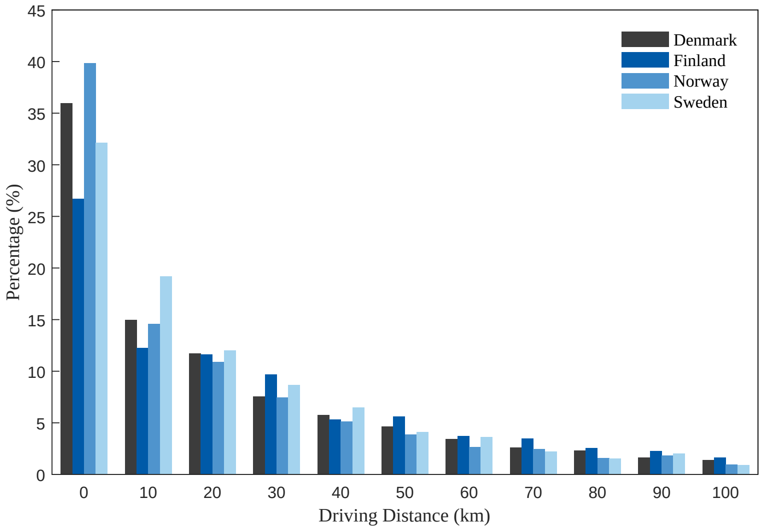


Figure 3.6: Daily Driving Distance Distribution in the Nordic Region on Weekends

driving distances on both weekdays and weekends. The daily driving distance will not only have important impacts on the EV battery sizing but also the EV charging energy planning to the power system. The higher driving distance in Finland will possibly lead to higher pressure for the energy planning of the EV charging. However, the generally low daily driving distance is conducive to the EV promotion and the EV integration to the power system in the Nordic region.

3.4 Charging Availability

In the integration study of EVs, the charging or discharging availability of EVs is also very important. The EV availability indicates the available time slot of the EVs when they are parked and can be connected to the grid for charging or discharging operations during the day. With different EV charging and discharging possibility assumptions, two types of EV availabilities are analyzed in this study, including EV availability all day and EV availability at home. The EV availability all day refers to the situation that the EVs can be charged or discharged in a day whenever they are parked. On the other hand, EV availability at home refers to the situation that the EVs can only be charged or discharged when they are parked at home.

Besides the driving distance, the starting time and the end time, the driving records in the National Travel Surveys also provide the information of the starting position and the destination of the trips. According to the time and position information of all the trips of the day, the driving and parking status of the vehicle can be determined in minute. Fig.3.7 shows the examples of the status of a vehicle along the day with the two different conditions. The status shown in the first plot in Fig.3.7 is the driving and parking status of the vehicle all day regardless of the parking place, which is associated with the EV availability all day. The status shown in the second plot in Fig.3.7 refers to the driving and home parking status of the vehicle which is associated with the EV availability at home.

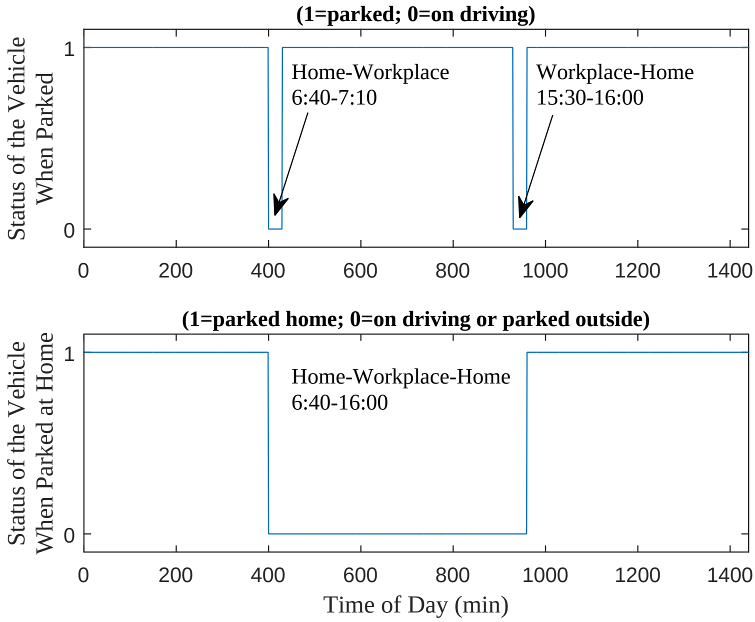


Figure 3.7: Driving and Parking Status of a Vehicle along the Day

Based on the status of the vehicles in every minute, the EV availabilities are calculated by hour and by quarter accordingly. They show the percentages of the EVs available for charging or discharging during the specific period of the day. The availabilities of all the vehicles are averaged to obtain the mean EV availabilities along the day.

The EV availability shows the possibility of the EV to be available for the integration operations to the grid during the specific period of the day. The EV availabilities vary with different charging/discharging supports of the power grid. In this study, two types of EV availabilities are investigated with two assumptions on the EV charging/discharging condition as indicated in Fig.3.7. The two types of EV availabilities include EV availability all day and EV availability at home as mentioned before.

The EV availability all day is determined according to the parking status of the vehicles. The vehicles are considered available for the grid integration operations when they are parked throughout the day. The EV availabilities all day by hour of the four Nordic countries on weekdays and weekends are shown in Fig.3.8 and Fig.3.9, respectively. It is shown that the EV availability all day of all the four Nordic countries on both weekdays and weekends are at a high level. For most of the time in a day, the average availabilities in all the four countries are over 90% except that it is about 89% in Sweden at around 5 pm on weekdays.

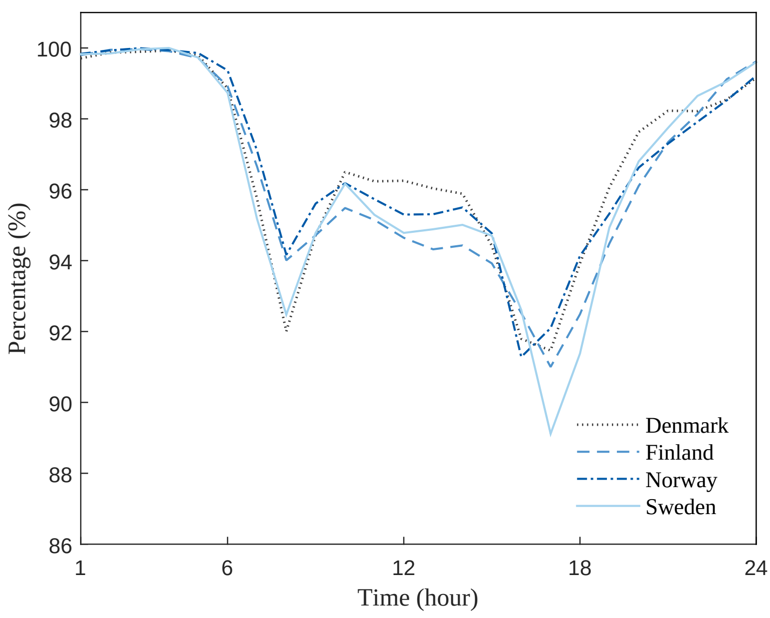


Figure 3.8: EV Availabilities All Day in the Nordic Region on Weekdays

The EV availabilities all day in all the four Nordic countries have similar patterns. On weekdays, there are two obvious valleys in curves of the EV availability all day, one in the morning at about 8 am and the other one in the afternoon at about 4-5 pm. Such characteristic is consistent with the traffic hours when people go to work in the morning and come home from work in the afternoon. On weekends, the curves of the EV availability all day are smoother. The EV

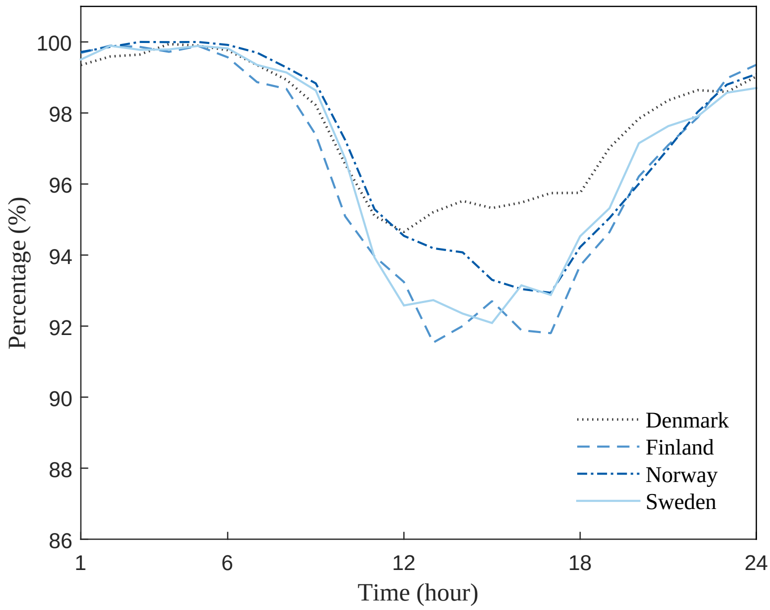


Figure 3.9: EV Availabilities All Day in the Nordic Region on Weekends

availabilities start to drop gradually in the morning and climb up steadily in the evening. Different from the case on weekdays, the EV availabilities do not increase again in the morning and stay on a plateau in the middle of the day on weekends. Such difference is because that there are very few driving behaviors for work on weekends. Therefore, the W-shape curves which are closely related to the driving and parking behaviors for work commutes on weekdays do not show up on weekends.

In certain studies of EVs, such as the research on EV home charging, only the home parking status of the vehicle is of interest and the EV availability at home shall be used in such studies. For the EV availability at home, the vehicles are considered available for the grid integration operations only when they are parked at home. The EV availabilities at home of the four Nordic countries on weekdays and weekends are shown in Fig.3.10 and Fig.3.11 respectively. The EV availabilities at home have much lower values than the EV availabilities all day in all the four Nordic countries in the daytime.

The lowest availabilities drop to the range around 50% on weekdays and 70% on weekends. The EV availabilities at home have similar patterns and values in the Nordic region. On weekdays, the EV availabilities at home in the Nordic region start to decrease in the morning at about 7 am, stay at a relatively low

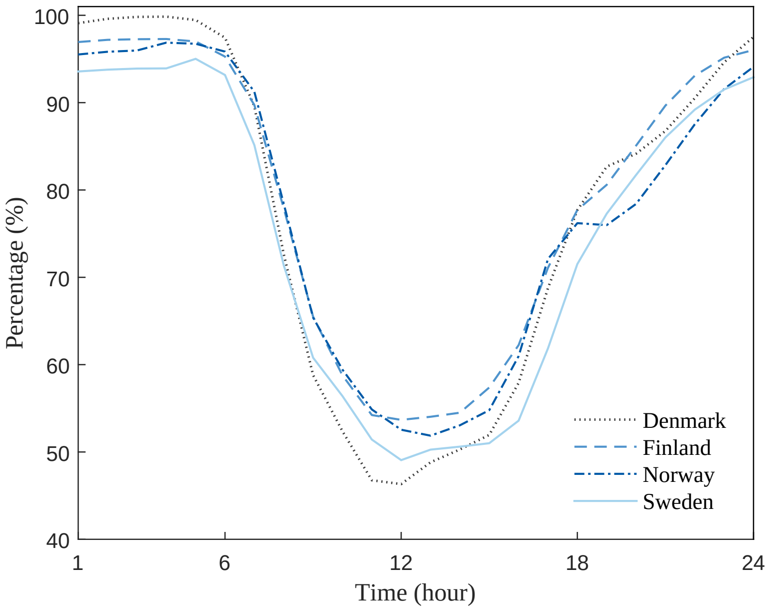


Figure 3.10: EV Availabilities at Home in the Nordic Region on Weekdays

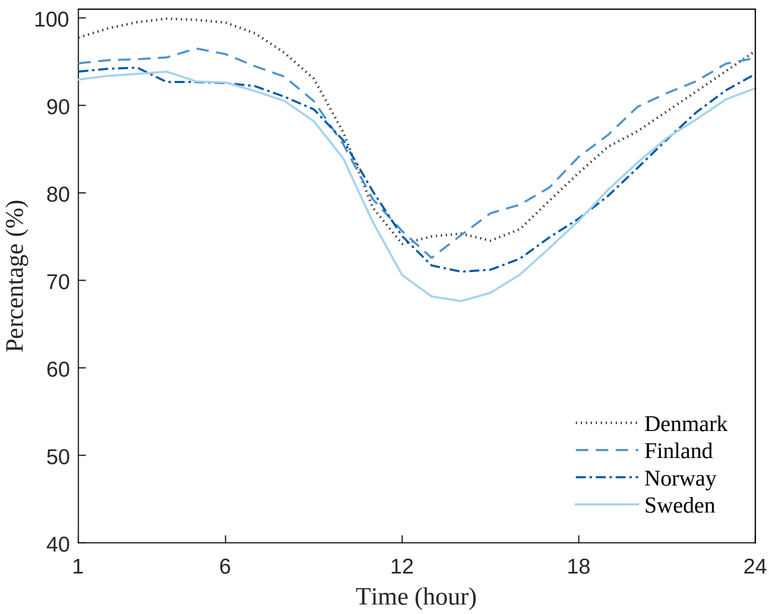


Figure 3.11: EV Availabilities at Home in the Nordic Region on Weekends

level and increase again in the afternoon when people start to return home. On weekends, the curves of the EV availability at home are smoother which is similar to the situation of the EV availability all day.

The EV availabilities are important to the EV integration study as they indicate the possibilities of the EV charging or scheduling. The results suggest that most of the vehicles can be scheduled during the night time. Such characteristic supports the ideas of shifting the EV charging load to the low-demand period and EV coordinated scheduling with wind power at night.

Chapter 4

Electrical Demand of EVs and HPs in Non-market Environments

In this chapter, the electrical demand of EVs and HPs under non-market environments in the Nordic region is studied. For EVs, the uncontrolled charging and timed charging demand is investigated. The driving patterns of the EVs are obtained from the National Travel Surveys of the Nordic countries as discussed in Section 3. For HPs, the electrical demand with a least-energy-consumption control scheme in the Nordic region is simulated.

4.1 EV Charging Demand under Non-market Environments in the Nordic Region

With large scale deployment of EVs, the power and energy demand of EVs will have a strong impact on the power system. The study on the impacts of the EV charging on the power system started in 1970s [44]. A number of studies have been carried out on the topic ever since [45–48]. In most of the studies, either at a national scale or a regional scale, the energy consumption or the charging availability of the vehicles was estimated without considering the actual driving patterns of the vehicles. Such assumptions might lead to inaccurate results of the EV charging analysis.

Regarding the Nordic area, the charging demand of EVs was studied in different countries. The work in [49, 50] studies the EV charging demand based on the case of the Danish island of Bornholm. The study in [51] presents the EV fleet integration in Bornholm with the Virtual Power Plant (VPP) concept. The study in [52] builds an optimal charging model according to the survey data of Western Denmark. The study in [53] gives an estimation of the charging cost of EVs in the Finnish context. The work in [54] studies the stochastic charging load of the plug-in hybrid electric vehicles (PHEVs) in Finland.

At present, a comprehensive study of the daily charging demand of EVs based on the actual driving behaviors for the Nordic area is missing. Such a study of the EV charging demand is essential to both the short term operations and long term planning of the power system if there is a considerable deployment of EVs.

In this section, the EV charging demand under non-market environment is modeled with the driving patterns obtained from the National Travel Surveys of the Nordic countries. The time resolution of the EV charging analysis in this section is one hour. The energy used per km for a home passenger car is typically between 120Wh/km and 180Wh/km [55]. In the analysis, an average energy consumption rate of 150Wh/km is used to calculate the energy consumption of the studied vehicles. The charging power is assumed to be 10kW.

4.1.1 Uncontrolled Charging Demand of EVs in the Nordic Region

Uncontrolled EV charging is the most common charging patterns at present. It is assumed that the EVs are charged whenever they are parked in this case. The electrical demand of uncontrolled EV charging in the Nordic region is studied. The charging energy requirement is determined by the energy consumption of the driving activities. The average demand of uncontrolled EV charging on weekdays in the Nordic region is as shown in Fig.4.1. During the weekdays, the charging demand of all the four Nordic countries shares a similar trend. There are two peaks in the EV charging load patterns of uncontrolled charging, one at 8-10 am in the morning and the other one at 5-8 pm in the evening and the latter one is higher in amplitude. The shape of the load curve is consistent with people's driving requirements for the daily commute between home and workplaces.

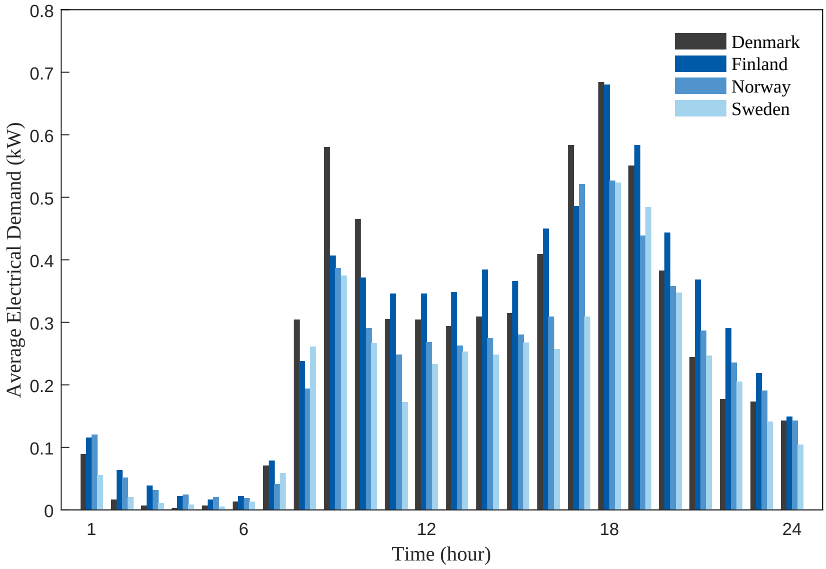


Figure 4.1: Average Uncontrolled EV Charging Demand on Weekdays in the Nordic Region

The average demand of uncontrolled EV charging on weekends in the Nordic region is as shown in Fig.4.2. The charging demand on weekends shows obvious differences from that on the weekdays. The charging load on weekends starts to rise rapidly in the late morning and the majority of the charging happens in the afternoon and evening when the people arrive home. Due to a higher driving distance, the average charging demand of Finland on weekends is distinctly higher than the other three countries.

4.1.2 Uncontrolled Home Charging Demand of EVs in the Nordic Region

The electrical demand of uncontrolled home charging of EVs in the Nordic region is also studied. It is assumed that the EVs are charged when they are parked at home. The average demand of uncontrolled EV home charging on weekdays in the Nordic region is as shown in Fig.4.3. It has different patterns from the case of the uncontrolled charging all day during the weekdays as shown in Fig.4.1. The peaks in the morning in the case of uncontrolled charging all day do not exist any more for home charging. The EV charging demand starts to increase in the afternoon and come to the peak in the evening from 5 to 8 pm when

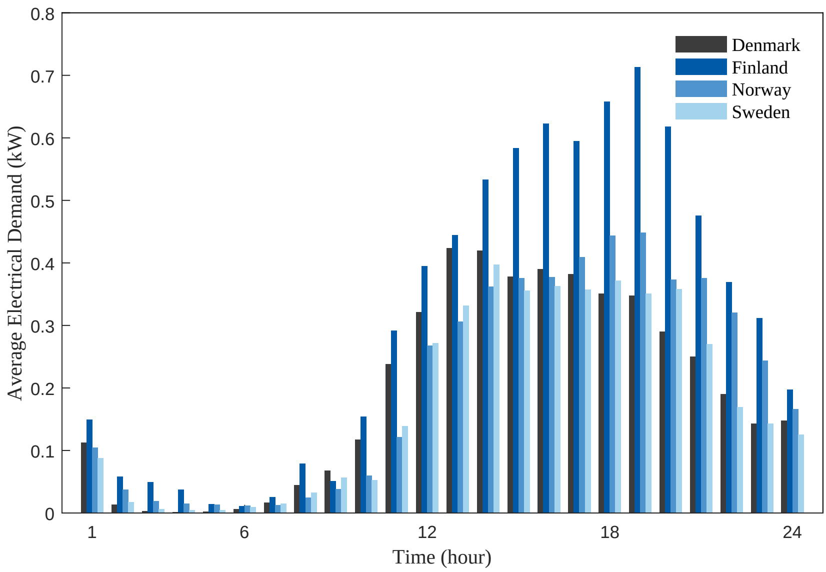


Figure 4.2: Average Uncontrolled EV Charging Demand on Weekends in the Nordic Region

people reach home from work.

The average demand of uncontrolled EV Home charging on weekends in the Nordic region is as shown in Fig.4.4. On weekends, the demand of the uncontrolled charging at home have similar patterns with the case of the uncontrolled charging all day as shown in Fig.4.2.

4.1.3 Timed Charging Demand of EVs in the Nordic Region

In order to prevent the overlap of the peak load of the EV charging with the conventional demand in the uncontrolled charging cases, a delayed charging scheme is usually introduced. Timed charging is one of the most common delayed charging patterns. It refers to a scheduled charging at specific time periods when the conventional demand of the power system is low. In this study, the EVs are assumed to be charged after 21:00 of the day when they are parked.

The average demand of timed EV charging on weekdays and weekends in the Nordic region is shown in Fig.4.5 and Fig.4.6, respectively.

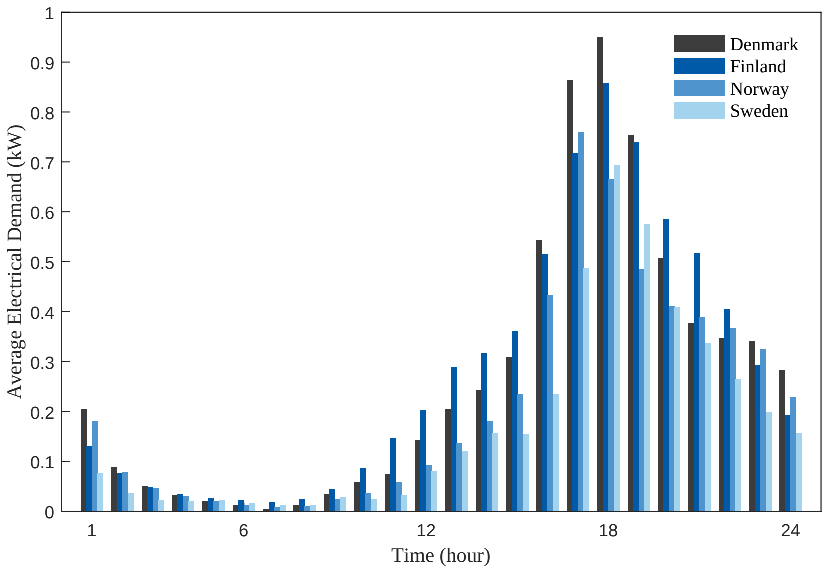


Figure 4.3: Average Uncontrolled EV Home Charging Demand on Weekdays in the Nordic Region

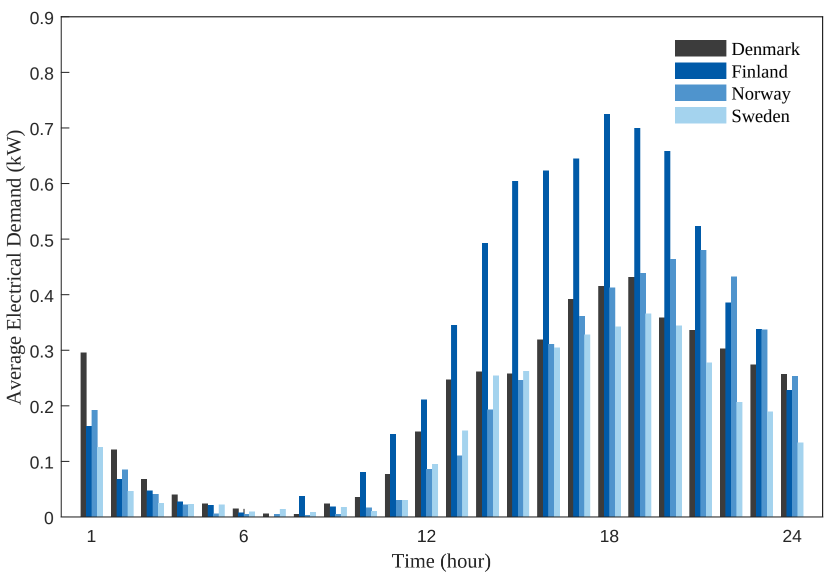


Figure 4.4: Average Uncontrolled EV Home Charging Demand on Weekends in the Nordic Region

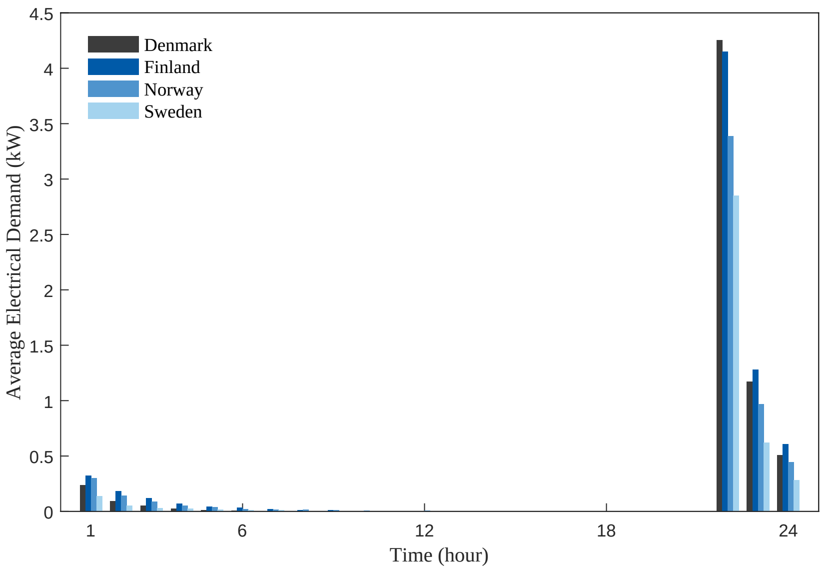


Figure 4.5: Average Timed EV Charging Demand on Weekdays in the Nordic Region

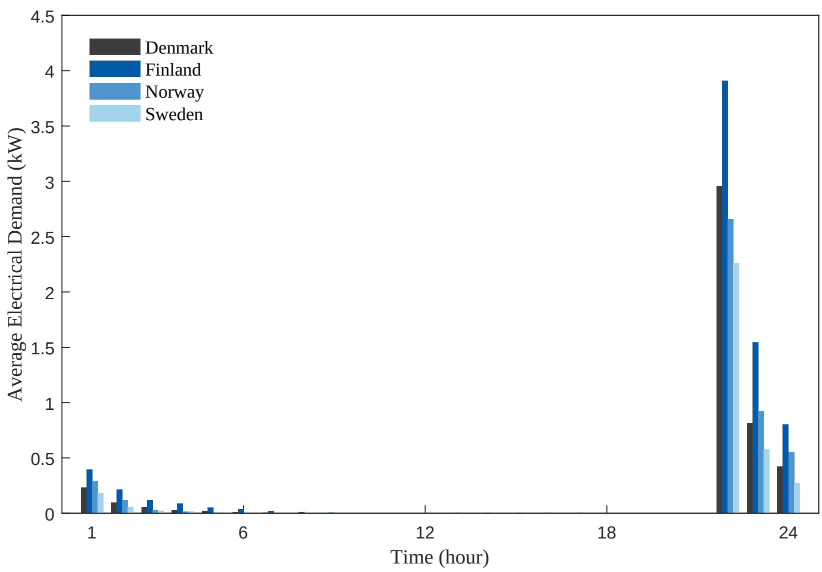


Figure 4.6: Average Timed EV Charging Demand on Weekends in the Nordic Region

As the vehicles are only charged after 9 pm in the evening, most of the charging demand converges in the short time slot from 9 to 11 pm and consequently form a steep spike in this period. The timed charging demand on both weekdays and weekends has such a load pattern. The differences between the driving patterns does not effect the charging demand significantly due to the fact that most of the daily driving behaviors have already been finished after the time line for the charging. Therefore, with timed charging scheme, the EVs tend to be charged together and create a peak demand correspondingly.

4.2 HP Demand with Least-Energy-Consumption Control in the Nordic Region

4.2.1 Thermal Dynamics of the House Heating with HPs

The demand of the HPs is dependent on the heating requirements of the households. Domestic houses are heated by the output of the HPs and the solar radiation. Meanwhile, they exchange heat with the exterior environment through thermal radiation and ventilation all the time. For simplification, the thermal model of a house can be comprised of three parts, including the interior of the house, the surface of the house including walls and windows, and the exterior. Such thermal dynamics of the houses with air source heat pumps (ASHPs) can be described by the differential equations below related to the interior air temperature, the ambient air temperature, the surface temperature of the house, the output of the HP, the solar radiation and the heat transfer coefficients (HTC) between the three parts of the houses [56].

$$\frac{\mathrm{d}T_{in}}{\mathrm{d}t} = \frac{1}{C_{in}} \left[Q_h + \xi_s \cdot W \cdot Q_s + C_{is}\left(T_{su} - T_{in}\right) + C_{ie}\left(T_{ex} - T_{in}\right)\right] \tag{4.1}$$

$$\frac{\mathrm{d}T_{su}}{\mathrm{d}t} = \frac{1}{C_{su}} \left[\xi_s \cdot E \cdot Q_s + C_{is}\left(T_{in} - T_{su}\right) + C_{se}\left(T_{ex} - T_{su}\right)\right] \tag{4.2}$$

where T_{in} is the temperature of the interior of the house; T_{su} is the temperature of the surface of the house; T_{ex} is the ambient temperature of the house; Q_h is the heating output of the heat pump; Q_s is the solar radiation; W is the window area of the house; E is the exterior wall area of the house; ξ_s is the efficiency of the solar radiation; C_{in} is the heat capacity of the interior of the house; C_{su} is the heat capacity of the surface of the house; C_{ie} is the heat transfer coefficient between house interior and exterior; C_{is} is the heat transfer coefficient between house interior and surface; C_{se} is the heat transfer coefficient between house surface and exterior.

Eqn.4.1 and Eqn.4.2 describe the thermal dynamics of different parts of the house. Given the output of the heat pump and the environmental circumstances, the temperature of the house can be calculated according to the differential equations.

4.2.2 HP Demand with Least-Energy-Consumption Control in the Nordic Region

4.2.2.1 Mathematical Modeling

A common control of the heating from HP is the least-energy-consumption control. The objective of the control is to minimize the heating energy consumption considering the heating requirements of the house. The model can be formulated as follows.

$$\min_{x_t} \sum_{t \in T} x_t \tag{4.3}$$

Subject to

$$T_{in}^{-} \leqslant T_{in,t} \leqslant T_{in}^{+} \quad \forall t \in T \tag{4.4}$$

$$Q_{h,t} \leqslant Q_h^{+} \quad \forall t \in T \tag{4.5}$$

$$Q_{h,t} = x_t COP_h \quad \forall t \in T \tag{4.6}$$

$$x_t \geqslant 0 \quad \forall t \in T \tag{4.7}$$

where x_t is the electrical demand of the HP at time t; $T_{in,t}$ is the temperature of the interior of the house at time t; T_{in}^{-} and T_{in}^{+} is the lower and upper temperature limits of the house interior; $Q_{h,t}$ is the heat output of the HP at time t; Q_h^{+} is the heat output limit of the HP; COP_h is the coefficient of performance of the HP; T is the set of time intervals for the control.

The objective of the energy plan is to minimize the energy consumption as Eqn.4.3 subject to the temperature requirement constraint 4.4, the HP heating output limit constraint 4.5, the HP coefficient of performance constraint 4.6

and the HP energy consumption non-negativity constraint 4.7. For constraint 4.4, the house interior temperature is limited with the specified range. For constraint 4.5, the HP heating output is limited by its capacity. For the HP coefficient of performance constraint 4.6, the relation of the HP heating output and its electricity consumption is depicted by the HP coefficient of performance COP_h.

The indoor temperature of the house $T_{in,t}$ is calculated according to the thermal dynamics described in Section 4.2.1. In order to integrate the differential equations of the thermal dynamics in the optimization, Eqn.4.1 and Eqn.4.2 are linearized as Eqn.4.8 and Eqn.4.9.

$$\frac{T_{in,t} - T_{in,t-1}}{\Delta t} = \frac{Q_{h,t} + \xi_s W Q_{s,t} + C_{is}\left(T_{su,t} - T_{in,t}\right) + C_{ie}\left(T_{ex,t} - T_{in,t}\right)}{C_{in}} \tag{4.8}$$

$$\frac{T_{su,t} - T_{su,t-1}}{\Delta t} = \frac{\xi_s E Q_{s,t} + C_{is}\left(T_{in,t} - T_{su,t}\right) + C_{se}\left(T_{ex,t} - T_{su,t}\right)}{C_{su}} \tag{4.9}$$

where $T_{su,t}$ is the temperature of the surface of the house at time t; $T_{ex,t}$ is the ambient temperature of the house at time t; $Q_{h,t}$ is the heating output of the heat pump at time t; $Q_{s,t}$ is the solar radiation at time t; Δt is the time interval of the optimization.

4.2.2.2 Scenario Description

A numerical study on the electrical demand of HPs with the least-energy-consumption control in the winter of the Nordic region is carried out. Apparently, the residential heating demand is strongly correlated with the environment factors including the temperature and solar radiation as shown in the thermal dynamics described in Section 4.2.1. Consequently, the HP demand is correlated with the environmental parameters.

In order to obtain an understanding of the demand, a scenario for the winter in the Nordic region is analyzed in the numerical study. The environmental parameters of the scenario including the ambient temperature and solar radiation profiles adopt the data in Copenhagen, Helsinki, Stockholm and Oslo in January respectively. They are as listed in Tab.4.1. The interior temperature preference is set in the range 20-24°C. The COP of the HPs is set to be 3.1375. The capacity of the heat pumps is set according to the size of the houses. In the cases of Denmark, for the houses with an area less than 90m^2, the capacity of the heat pump is set to be 5kW; for the houses with an area between 90 to

Table 4.1: Environment Profiles in the Case Study of HP Demand in the Nordic Region

Hour	Ambient Temperature (°C)				Solar Radiation (W/m^2)			
	DK	FI	NO	SE	DK	FI	NO	SE
1	-2.0	-9.5	-8.0	-7.0	0	0	0	0
2	-2.3	-10.0	-6.6	-7.4	0	0	0	0
3	-2.6	-11.3	-6.5	-8.0	0	0	0	0
4	-2.6	-9.0	-7.5	-8.5	0	0	0	0
5	-2.6	-9.0	-7.5	-9.4	0	0	0	0
6	-2.6	-10.0	-8.0	-10.0	0	0	0	0
7	-2.7	-8.5	-8.0	-10.0	0	0	0	0
8	-2.9	-7.5	-7.1	-8.8	32.2	5.3	0	0
9	-2.7	-7.6	-6.5	-9.0	123.3	32.9	0	55.9
10	-2.0	-7.0	-7.0	-7.0	151.6	71.5	20.3	131.2
11	-1.5	-7.0	-6.0	-4.9	149.8	64.5	33.6	194.3
12	-0.9	-7.0	-6.0	-3.0	196.3	68.7	46.5	210.9
13	-0.3	-6.5	-5.0	-1.5	198.2	75.9	56.6	195.1
14	0.1	-6.0	-4.5	-1.0	173.0	44.5	31.4	120.1
15	-0.2	-6.0	-4.0	-0.5	98.1	6.1	12.1	58.7
16	-0.5	-6.0	-4.5	-1.5	16.1	0	0	3.3
17	-1.1	-6.0	-5.5	-3.3	0	0	0	0
18	-1.2	-6.5	-5.5	-4.5	0	0	0	0
19	-1.4	-7.0	-5.5	-5.5	0	0	0	0
20	-1.3	-6.5	-6.0	-6.4	0	0	0	0
21	-1.3	-6.6	-7.0	-7.5	0	0	0	0
22	-1.4	-7.0	-7.5	-8.5	0	0	0	0
23	-1.3	-8.5	-6.0	-10.0	0	0	0	0
24	-1.1	-8.0	-8.0	-10.0	0	0	0	0

150m^2, the capacity of the heat pump is set to be 10kW; for the houses with an area over 150m^2, the capacity of the heat pump is set to be 15kW. In the cases of the other three countries, for the houses with an area less than 140m^2, the capacity of the heat pump is set to be 10kW; for the houses with an area between 140 to 200m^2, the capacity of the heat pump is set to be 15kW; for the houses with an area over 200m^2, the capacity of the heat pump is set to be 20kW.

The heat capacities and the heat transfer coefficients between the three parts of the house can be quantified according to the dimensions of the house [57].

$$C_i = 1.4 \times 10^4 A (J/K) \tag{4.10}$$

$$C_s = 3.6 \times 10^5 A (J/K) \tag{4.11}$$

$$C_{is} = 7.69 S (W/K) \tag{4.12}$$

$$C_{ie} = 0.34 V A H (W/K) \tag{4.13}$$

$$C_{ie} = \frac{7.69S(69.05 + 1.07A)}{7.69S - (69.05 + 1.07A)} (W/K) \tag{4.14}$$

4.2.2.3 Numerical Study Result

The average electrical demand of the HPs for the houses randomly sizing from 40-250m^2 in the study is as shown in Fig.4.7.

As shown in the figure, the demand of the HPs is higher in the evening and at night when the temperature is lower and there is no sun light. The demand drops in the middle of the day when the temperatures and the solar radiation are relatively high. The increasing HP demand in the evening coincides with the peak hours of the conventional demand of the power system which may stress the system. Besides, it is worth noting that the demand in Denmark is lower than the other three countries due to a more gentle environmental profile in Denmark.

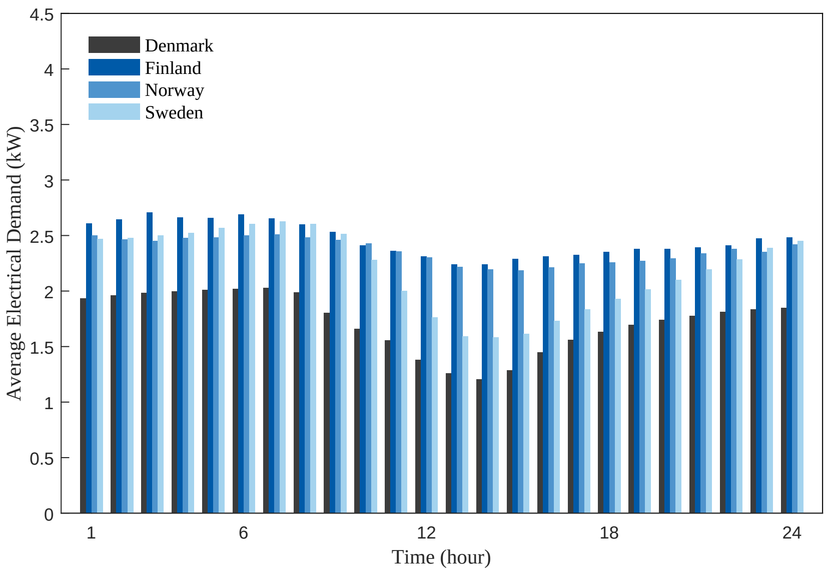


Figure 4.7: Average Electrical Demand of HPs in the Nordic Region

Chapter 5

Optimal Scheduling of EVs and HPs in the Day-ahead Market

In this chapter, the electrical demand of EVs and HPs is modeled under the day-ahead electricity market in the Nordic region. For aggregators of EVs and HPs, their objective of the day-ahead scheduling is to minimize the energy cost. For the EVs, in order to handle the stochastic features of the driving patterns, a chance constrained model is built and solved through a mixed-integer programming (MIP). For HPs, a robust optimization model is built to address the uncertainty in the weather forecast. In order to analyze the impacts of the EV and HP demand on the day-ahead market, an aggregative game model is built and analyzed.

5.1 Day-ahead Optimal Scheduling of EVs

5.1.1 Preliminary

The study in Section 4.1 has shown that with uncontrolled charging, the electrical demand of EVs coincides the same peak hours with the conventional demand in the power system. With timed charging, the electrical demand of EVs can be delayed to avoid the peak conventional demand. However, the time charging demand cannot fully cope with the low demand period of the power system to perform the "valley-fill" load pattern. The EV demand with timed charging congregates at a short period when most of the charging starts at the same time. In order to further utilized the flexibility of the EV charging, a promising approach is to introduce the EV charging demand to the electricity market. In this section, EV demand under the market circumstances is investigated. The day-ahead energy planning of the EV charging in the electricity spot market by the EV aggregators who handle the EV charging for their customers is modeled and analyzed.

The modeling of the EV charging demand in the day-ahead electricity market has been investigated in a number of studies [58–71]. However, in most of the previous work, the driving patterns of the EVs are assumed to be known or precisely forecast by the EV charging operators one day ahead during the energy planning of the EV charging. Such assumption is too strong for reality. In order to address such issue and handle the stochastic features of the EV charging due to the driving patterns of the vehicles, a chance constrained optimization model is built for the energy planning of the EV aggregators. The chance constrained optimization model is analyzed and formulated through MIP, which can therefore be solved efficiently with the commercial solvers at present. The EV aggregators in the study are assumed to be economically rational as price takers in the day-ahead electricity spot market and pursue a minimal cost of the charging in their energy planning while meeting the daily driving patterns of the customers.

5.1.2 Mathematical Modeling

In order to secure the energy needs for the next day's driving, the EV aggregators need to plan the EV charging schedule and submit the bids in the day-ahead energy market. The objective of the optimal charging of the aggregator is to minimize the charging cost while meeting the EV driving requirements. Therefore, the day-ahead scheduling of the EV charging from the aggregator is formulated as follows.

$$\min_{x_{v,t}} \sum_{t \in T} \sum_{v \in V} \alpha_t x_{v,t} \tag{5.1}$$

Subject to

$$e_v^- \leqslant \sum_{\tau=0}^{t} (x_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall v \in V, \forall t \in T \tag{5.2}$$

$$x_{v,t} \leqslant p^+ s_{v,t} \quad \forall v \in V, \forall t \in T \tag{5.3}$$

$$x_{v,t} \geqslant 0 \quad \forall v \in V, \forall t \in T \tag{5.4}$$

where α_t is the spot price of electricity at time t in the day-ahead market; $x_{v,t}$ is the charging energy of vehicle v at time t; $d_{v,t}$ is the driving energy consumption of vehicle v at time t; e_v^- is the lower limit of the state of charge (SOC) level of vehicle v; e_v^+ is the upper limit of the SOC level of vehicle v; e_v^0 is the initial SOC level of vehicle v; p^+ is the upper power limit of the EV charging; $s_{v,t}$ is the charging availability indicator of vehicle v at time t; V is the set of EVs of the aggregator; T is the set of time intervals for the planning.

The objective of the aggregator is to minimize the charging cost as Eqn.5.1 subject to the SOC limit constraint 5.2, the EV charging energy limit constraint 5.3 and the charging energy non-negativity constraint 5.4. For the SOC limit constraint 5.2, the EV SOC level is calculated through the cumulated charging energy and the driving energy consumption. In each time interval, the charging plan of each EV should meet the driving energy consumption while the SOC levels of the EV battery are within the specified range. For the charging energy limit constraint 5.3, the EV charging energy is constrained by the maximum power limit and the EV charging availability. The EV charging availability indicator $s_{v,t}$ shows the status of the EV at time t. It equals to 1 when the EV is parked and available for charging, and it equals to 0 when the EV is not available for charging, for example when it is being driven on the road.

In the deterministic model, it is assumed that the aggregators have perfect information of EV driving patterns for the next day. The aggregators need to precisely predict the driving requirement and the charging availability of the EVs before they carry out the energy planning and submit the bids in the day-ahead market. However, due to the randomness of the driving need, it is very difficult to perfectly predict the driving requirements and the charging availability of the EVs one day in advance. As a result, energy planning with deterministic modeling might not meet the actual driving requirements of the EVs. Because of inherent randomness of the driving requirements, there is a chance that the EV user needs to drive for a longer distance or start the trips earlier than expected. In such cases, the energy plan is unable to fulfill the actual driving need as the EV needs more energy or its available period for charging is shorter. Therefore, optimal energy planning for the EV charging based on a deterministic approach cannot be actually realized by the aggregators.

Chance constrained programming is a direct and efficient tool to handle such a predicament. The randomness of the driving patterns lies in constraint 5.2 and 5.3.The driving distance $d_{v,t}$ and the charging availability $s_{v,t}$ are stochastic parameters dependent on the driving pattern of the EV. The two constraints can be reformulated in a chance constrained framework as Eqn.5.5.

$$Pr\left\{\begin{aligned} e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - d_{v,\tau}) + e_v^0 \\ \sum_{\tau=0}^{t}(x_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \\ x_{v,t} \leqslant p^+ s_{v,t} \end{aligned} \quad \forall t \in T\right\} \geqslant 1-\epsilon \quad \forall v \in V \tag{5.5}$$

The chance constrained model of the optimal charging of aggregator is formed by objective 5.1 subject to the charging energy non-negativity constraint 5.4 and the probabilistic constraint 5.5. The probabilistic constraint 5.5 guarantees that the failure probability of the charging meeting the driving requirements is under the predetermined confidence parameter ϵ for each EV.

As neither of the stochastic parameters $d_{v,t}$ nor $s_{v,t}$ in the chance constrained model follows a Gaussian distribution and their elements with different time index are correlated with each other, such chance constrained optimization problems are hard to solve [72]. Notice that

- the constraints are linear and the stochastic parameters are not the multipliers of the variables $x_{v,t}$
- the stochastic parameters have finite distribution
- the domain of the optimization is bounded

the chance constrained optimization can be solved by a mixed-integer programming method proposed by [72, 73]. A realization of the possible driving pattern is depicted by the parameter $d_{r,t}$ and $s_{r,t}$ associated with the probability π_r. A binary variable $z_{v,r}$ is introduced for each driving pattern realization and the probabilistic constraint 5.5 can be reformulated as follows.

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - d_{r,\tau}) + e_v^0 + z_{v,r}\sum_{\tau=0}^{t} d_{r,\tau} \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.6}$$

$$\sum_{\tau=0}^{t}(x_{v,\tau} - d_{r,\tau}) + e_v^0 \leqslant e_v^+ + z_{v,r}\sum_{\tau=0}^{t}(p^+ - d_{r,\tau}) \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.7}$$

$$x_{v,t} \leqslant p^+ s_{v,t} + p^+ z_{v,r} \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.8}$$

$$\sum_{r \in R}(\pi_r z_{v,r}) \leqslant \epsilon \quad \forall v \in V, \forall t \in T \tag{5.9}$$

where $d_{r,t}$ is the driving energy consumption of the vehicle at time t for realization r of the driving patterns; $s_{r,t}$ is the charging availability indicator of the vehicle at time t for realization r of the driving patterns; R is the set of realizations of the driving patterns of the vehicles.

When the binary variable $z_{v,r} = 0$, constraint 5.6 to 5.8 can be changed to the form in the following equations (Eqn.5.10 to 5.12) and guarantee the constraints for the driving pattern realization r are satisfied.

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - d_{r,\tau}) + e_v^0 \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.10}$$

$$\sum_{\tau=0}^{t}(x_{v,\tau} - d_{r,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.11}$$

$$x_{v,t} \leqslant p^+ s_{v,t} \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.12}$$

For constraint 5.10 and 5.11, the EV SOC level is constrained within the specified range with driving pattern realization r in each time interval. For constraint 5.12, the charging availability with realization r is met in each time interval. The driving pattern realization r is therefore satisfied by the charging with the constraints.

When the binary variable $z_{v,r} = 1$, constraint 5.6 to 5.8 can be changed to the form in the following equations (Eqn.5.13 to 5.15) and they are automatically satisfied in the domain of the optimization.

$$e_v^- \leqslant \sum_{\tau=0}^{t} x_{v,\tau} + e_v^0 \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.13}$$

$$e_v^0 \leqslant e_v^+ + \sum_{\tau=0}^{t}(p^+ - x_{v,\tau}) \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.14}$$

$$x_{v,t} \leqslant p^+(1 + s_{v,t}) \quad \forall v \in V, \forall r \in R, \forall t \in T \tag{5.15}$$

Constraint 5.13 to 5.15 are always satisfied in the domain of the optimization ($0 \leqslant x_{v,t} \leqslant p^+$) given a reasonable SOC condition that the SOC level of the EV battery is within the limit ($e_v^- \leqslant e_v^0 \leqslant e_v^+$). Therefore, the driving pattern realization r has no constraints on the charging plan when the corresponding binary variable $z_{v,r} = 1$. Nevertheless, such driving pattern realizations are constrained by the probabilistic limit as shown in constraint 5.9. In constraint 5.9, π_r is the probability of the realization r of the possible driving patterns. The knapsack constraint 5.9 is equivalent to the probabilistic constraint as shown in Eqn.5.16 and therefore the original probabilistic constraint 5.5 is satisfied.

$$\sum_{r \in R} \pi_r(1 - z_{v,r}) \leqslant 1 - \epsilon \quad \forall v \in V, \forall t \in T \tag{5.16}$$

For the probability of each possible driving pattern realization, $\pi_r \subset [0, 1]$ ($\forall r \in R$). Therefore, the binary variable for the realization r of the possible driving patterns $z_{v,r} = 0$ when $\pi_r > \epsilon$, otherwise constraint 5.9 cannot be satisfied. Then the set of the possible driving patterns realizations R can be divided into two subsets: the subset of possible driving pattern realizations with a probability over confidence parameter $R_+ = \{r \in R : \pi_r > \epsilon\}$ and the subset of possible driving pattern realizations with a probability less than or equal to confidence parameter $R_- = \{r \in R : \pi_r \leqslant \epsilon\}$. In order to tighten the constraints, Eqn.5.6 to 5.9 can be formulated as Eqn.5.18 to 5.24 and the number of the binary variables is reduced. Consequently, the optimization of the aggregator can be reformulated to the following model.

$$\min_{x_{v,t}} \sum_{t \in T} \sum_{v \in V} \alpha_t x_{v,t} \tag{5.17}$$

Subject to

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - d_{r_1,\tau}) + e_v^0 \quad \forall v \in V, \forall r_1 \in R_+, \forall t \in T \tag{5.18}$$

$$\sum_{\tau=0}^{t}(x_{v,\tau} - d_{r_1,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall v \in V, \forall r_1 \in R_+, \forall t \in T \tag{5.19}$$

$$x_{v,t} \leqslant p^+ s_{r_1,t} \quad \forall v \in V, \forall r_1 \in R_+, \forall t \in T \tag{5.20}$$

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - d_{r_2,\tau}) + e_v^0 + z_{v,r_2}\sum_{\tau=0}^{t} d_{r_2,\tau} \quad \forall v \in V, \forall r_2 \in R_-, \forall t \in T \quad (5.21)$$

$$\sum_{\tau=0}^{t}(x_{v,\tau} - d_{r_2,\tau}) + e_v^0 \leqslant e_v^+ + z_{v,r_2}\sum_{\tau=0}^{t}(p^+ - d_{r_2,\tau}) \quad \forall v \in V, \forall r_2 \in R_-, \forall t \in T \quad (5.22)$$

$$x_{v,t} \leqslant p^+ s_{r_2,t} + p^+ z_{v,r_2} \quad \forall v \in V, \forall r_2 \in R_-, \forall t \in T \quad (5.23)$$

$$\sum_{r_2 \in R_-}(\pi_{r_2} z_{v,r_2}) \leqslant \epsilon \quad z_{v,r_2} \in \{0,1\} \quad \forall v \in V, \forall t \in T \quad (5.24)$$

$$x_{v,t} \geqslant 0 \quad \forall v \in V, \forall t \in T \quad (5.25)$$

For constraint 5.18 to 5.20, the driving pattern realization r_1 is met by the charging plan. For constraint 5.21 to 5.23, the driving pattern realization r_2 is met when the binary variable $z_{v,r_2} = 0$, and the constraints are always satisfied in the domain of the optimization when $z_{v,r_2} = 1$. Constraint 5.24 guarantees that the failure probability of the charging plan is under the confidence parameter ϵ the same as constraint 5.5. The optimization problem is therefore formulated through a typical mixed-integer programming model and can be solved by a number of commercial solvers [74].

5.1.3 Numerical Case Study

The case of Denmark with the chance constrained optimal EV charging in the day-ahead market is studied. The key parameters of the EVs in the study are listed in Tab.5.1. The electricity spot prices used in the case study is as shown in Appendix B. The driving patterns of the vehicles are obtained from the National Travel Surveys of Denmark as described in Section 3. The confidence parameter in the chance constrained model is set to be 5% in the study.

The average demand of the EV charging on weekdays in Denmark is as shown in Fig.5.1. It is shown that the charging behaviors happen at night when the conventional demand of the system is low. It is mainly due to the fact that the electricity spot prices are low in the period. The EV charging occurs at the moment for a minimum charging cost. Further, in order to guarantee the driving requirements of the EVs in the day, the charging tends to happen at night before the daily driving behaviors start.

Table 5.1: EV Parameters in Case Study

Parameter	Value
EV battery capacity	60kWh
Charging power limit	10kW
Energy consumption per km	150Wh/km
Lower SOC level limit	20%
Upper SOC level limit	85%

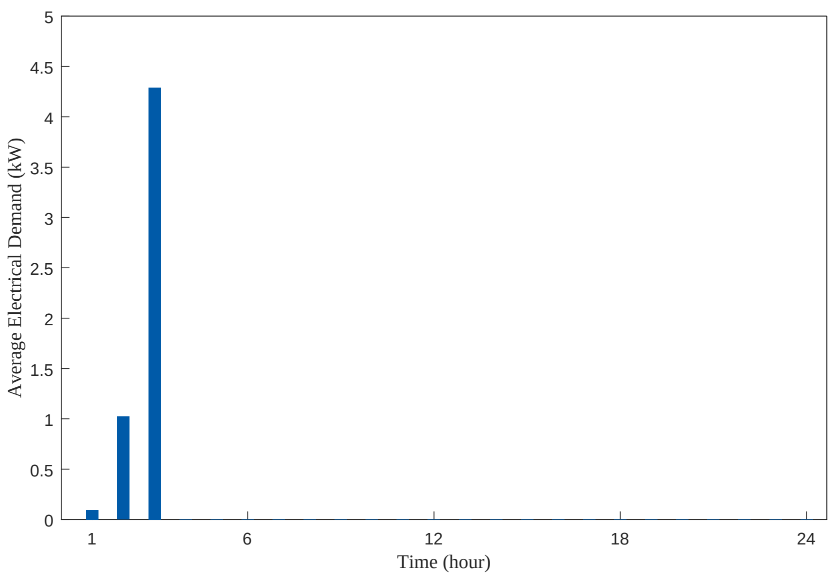


Figure 5.1: Average Electrical Demand of Optimal EV Charging in Denmark

5.2 Day-ahead Optimal Scheduling of HPs

5.2.1 Preliminary

The study in Section 4.2 has shown that the HP demand in a non-market environment is to some extent higher at night when the conventional demand is low and slightly lower in the middle day in the Nordic region. However, the flexibility of the HP at the demand side is not explored and utilized with such control scheme. The HP demand does not fully cope with the low demand period of the power system to perform the "valley-fill" load pattern. The increasing HP demand in the evening coincides with the peak hours of the conventional demand of the power system. In order to further utilized the flexibility of the HP demand, a potential approach is to introduce the HP demand into the electricity market. In this section, the HP demand under the market circumstances is investigated. The day-ahead energy planning of HP demand by the HP aggregators who handle the HP scheduling for their customers is analyzed and modeled through a robust optimization formulation in order to guarantee the heating demand. The HP aggregators are assumed to be economically rational as price takers in the day-ahead electricity market and pursue a minimal cost of the HP demand in their energy planning while fulfilling the necessary heating requirements of the customers.

5.2.2 Mathematical Modeling

For the HP scheduling in the day-ahead market, the objective of the aggregators is also to minimize the energy cost while meeting the necessary heating requirements. Therefore, the optimization of the HP aggregators can be formulated as follows.

$$\min_{x_{h,t}} \sum_{t \in T} \sum_{h \in H} \alpha_t x_{h,t} \tag{5.26}$$

Subject to

$$T_{in}^{-} \leqslant T_{in,h,t} \leqslant T_{in}^{+} \quad \forall h \in H, \forall t \in T \tag{5.27}$$

$$Q_{h,t} \leqslant Q_h^{+} \quad \forall h \in H, \forall t \in T \tag{5.28}$$

$$Q_{h,t} = x_{h,t} COP_h \quad \forall h \in H, \forall t \in T \tag{5.29}$$

$$x_{h,t} \geqslant 0 \quad \forall h \in H, \forall t \in T \tag{5.30}$$

where α_t is the spot price of the electricity at time t in the day-ahead market; $x_{h,t}$ is the electrical demand of the HP h at time t; $T_{in,h,t}$ is the temperature of the house interior of HP h; T_{in}^{-} and T_{in}^{+} is the lower and upper temperature limits of the house interior; $Q_{h,t}$ is the heat output of the HP h at time t; Q_h^{+} is the heat output limit of HP h; COP_h is the coefficient of performance of HP h; H is the set of the HPs of the aggregator, T is the set of time intervals for the planning.

The objective of the aggregator is to minimize the charging cost as Eqn.5.26 subject to the temperature requirement constraint 5.27, the HP heating output limit constraint 5.28, the HP coefficient of performance constraint 5.29 and the HP energy consumption non-negativity constraint 5.30. For constraint 5.27, the house interior temperature is limited with the specified range. For constraint 5.28, the HP heating output is limited by its capacity. For the HP coefficient of performance constraint 5.29, the relation of the HP heating output and its electricity consumption is depicted by the HP coefficient of performance COP_h.

The indoor temperature $T_{i,h,t}$ is calculated according to the thermal dynamics described in Section 4.2.1. In order to integrate the differential equations of the thermal dynamics in the optimization, Eqn.4.1 and Eqn.4.2 are linearized as follows.

$$\frac{T_{in,h,t} - T_{in,h,t-1}}{\Delta t} = \frac{Q_{h,t} + \xi_s W Q_{s,t} + C_{is}\left(T_{su,h,t} - T_{in,h,t}\right) + C_{ie}\left(T_{ex,t} - T_{in,h,t}\right)}{C_{in}} \tag{5.31}$$

$$\frac{T_{su,h,t} - T_{su,h,t-1}}{\Delta t} = \frac{\xi_s E Q_{s,t} + C_{is}\left(T_{in,h,t} - T_{su,h,t}\right) + C_{se}\left(T_{ex,t} - T_{su,h,t}\right)}{C_{su}} \tag{5.32}$$

where $T_{su,h,t}$ is the temperature of the house surface of the HP h at time t; $T_{ex,t}$ is the ambient temperature at time t; $Q_{h,t}$ is the heating output of the HP h at time t; $Q_{s,t}$ is the solar radiation at time t; Δt is the time interval of the optimization.

In the deterministic model mentioned above, it is assumed that the aggregators have a perfect forecast of the weather for the next day. At present, although a number of advanced numerical prediction methods have made the day-ahead weather forecasts more and more accurate, there inevitably remains uncertainty in the day-ahead weather forecasts [75, 76]. It is impossible for the aggregators to predict the weather perfectly one day ahead for the HP energy planning in real life. In such case, forecasts with scenarios can be used to provide margins to the prediction and robust optimization can be applied in order to guarantee the temperature requirements are met by the HP energy plan.

In the robust optimization model, the house interior temperature requirement constraint 5.27 is changed to the form as follows.

$$T_{in}^{-} \leqslant T_{in,h,r,t} \leqslant T_{in}^{+} \quad \forall h \in H, \forall r \in R, \forall t \in T \tag{5.33}$$

where $T_{in,h,r,t}$ is the house interior temperature of HP h with weather profile r at time t; R is the set of weather forecast scenarios.

For all the scenarios of the weather forecast, the energy plan of the HPs meet the heating requirements and guarantee that the house interior temperature is within the specified range with constraint 5.33. Therefore, the mathematic model of the robust optimization of the aggregators for the day-ahead HP energy plan is as follows.

$$\min_{x_{h,t}} \sum_{t \in T} \sum_{h \in H} x_{h,t} \tag{5.34}$$

Subject to

$$T_{in}^{-} \leqslant T_{in,h,r,t} \leqslant T_{in}^{+} \quad \forall h \in H, \forall r \in R, \forall t \in T \tag{5.35}$$

$$Q_{h,t} \leqslant Q_h^{+} \quad \forall h \in H, \forall t \in T \tag{5.36}$$

$$Q_{h,t} = x_{h,t} COP_h \quad \forall h \in H, \forall t \in T \tag{5.37}$$

$$x_{h,t} \geqslant 0 \quad \forall h \in H, \forall t \in T \tag{5.38}$$

$$\begin{aligned} \frac{T_{in,h,r,t} - T_{in,h,r,t-1}}{\Delta t} =& \frac{1}{C_{in}} [Q_{h,t} + \xi_s W Q_{s,r,t} + C_{is} \left(T_{su,h,r,t} - T_{in,h,r,t}\right) + \\ & C_{ie} \left(T_{ex,r,t} - T_{in,h,r,t}\right)] \quad \forall h \in H, \forall r \in R, \forall t \in T \end{aligned} \tag{5.39}$$

$$\begin{aligned} \frac{T_{su,h,r,t} - T_{su,h,r,t-1}}{\Delta t} =& \frac{1}{C_{su}} [\xi_s E Q_{s,r,t} + C_{is} \left(T_{in,h,r,t} - T_{su,h,r,t}\right) + \\ & C_{se} \left(T_{ex,r,t} - T_{su,h,r,t}\right)] \quad \forall h \in H, \forall r \in R, \forall t \in T \end{aligned} \tag{5.40}$$

where $T_{su,h,r,t}$ is the house surface temperature of HP h with weather profile r at time t; $T_{ex,r,t}$ is the exterior temperature in weather profile r at time t; $Q_{s,r,t}$ is the solar radiation in weather profile r at time t.

5.2.3 Numerical Case Study

A numerical study on the electrical demand of HPs with the least-cost optimal control in the winter of Denmark is carried out. The environmental expectations used in the study are as the Danish profiles shown in Section 4.2.2.2 with a temperature margin of ±3°C, a solar radiation margin of ±15% and a phase margin of ±1 hour. The interior temperature preference is set in the range 20-24°C. The capacity of the heat pumps is set according to the size of the houses. For the houses with an area less than 90m^2, the capacity of the heat pump is set to be 5kW; for the houses with an area between 90 to 150m^2, the capacity of the heat pump is set to be 10kW; for the houses with an area over 150m^2, the capacity of the heat pump is set to be 15kW. The average electrical demand of the HPs for the houses randomly sizing from 40 to 250m^2 with a uniform distribution in the study is as shown in Fig.5.2.

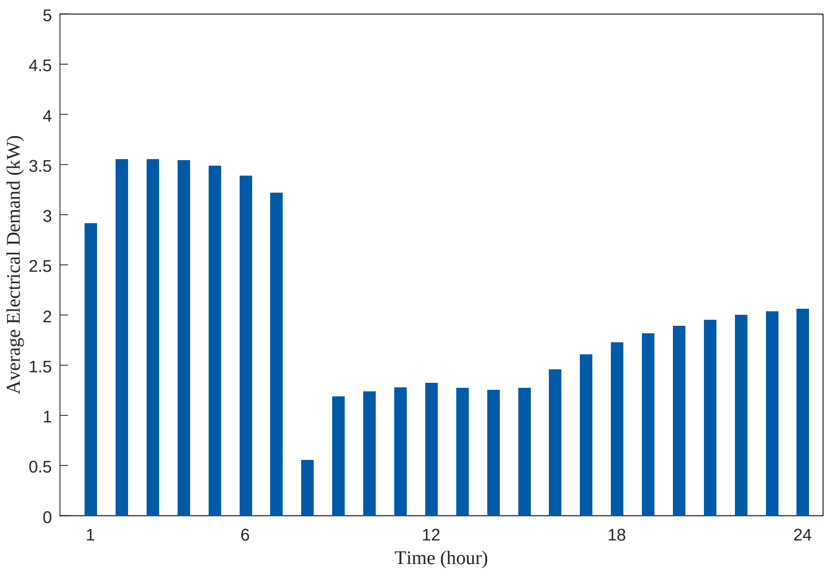


Figure 5.2: Average Electrical Demand of Optimal HP Energy Planning in Day-ahead Market in Denmark

As shown in Fig.5.2, the peak demand of the HPs happens at night when the electricity spot prices are low. The demand in the day can therefore be reduced in the day when the prices are relatively high. Due to the heating requirement limit, the HP demand increases gradually in the evening.

5.3 Demand Model of EVs and HPs with Aggregative Game

5.3.1 Preliminary

The results of the optimal energy planning of EVs and HPs in the day-ahead market have shown that with market based energy planning the load of EVs and HPs can be shifted from the high-demand period of the conventional demand in the day and in the evening to the low-demand period at night. In the models of the optimal energy planning of EVs and HPs in Section 5.1 and Section 5.2, the aggregators of EVs and HPs are assumed as price takers. Such assumption is fair when the numbers of EVs and HPs are relatively small in the grid. However, when there is a high penetration level of EVs and HPs in the power system, their demand is considerable to the conventional demand. In such case, the demand of EVs and HPs will have impacts on the spot prices of the electricity in the day-ahead market. In order to include such impacts on the spot prices in the modeling of the EV and HP demand, an aggregative game model is built and presented in this section.

At present, there are a few studies focusing on the demand response of EVs with game theory in the electricity market. The work in [77] formulates the game of EV charging management to describe the competition of the time-flexible load from EV in the future demand-side management (DSM) system. The work in [78] formulates a game theoretic framework designed for simulating EV aggregations' strategy in a competitive market and proposes a decision model to draw the pricing strategy for the retail market and biding strategy for the pool market. The work in [79] proposes a static non-cooperative game formulation of distributed charging in EV networks to model the interaction between several EV which are connected to a common residential distribution transformer. The work in [80, 81] introduces a mean field game formulation for the competition of EV charging in the smart grid energy market, providing a formal description of the competitive interaction of EV owners based on collective price incentives. The work in [82, 83] develops a decentralized charging control for large populations of plug-in electric vehicles (PEVs). It applies the principle of Nash Certainty Equivalence for the overnight "valley-fill" charging control. The work in [84] also proposes a distributed multi-agent EV charging control method based on the Nash Certainty Equivalence Principle.

For most of the work in the previous literature, the detailed driving patterns of the EVs are not considered. Further, most of them only consider a single type of flexible demand (for example EV charging) in the electricity market. However, when there are multiple types of flexible demand in the game, it is difficult to integrate them at the same time in the competition frameworks of the present studies. In this section, an aggregative game model is proposed to integrate the flexible demand of both EVs and HPs while considering the energy requirements with detailed driving patterns and environmental profiles.

5.3.2 Mathematical Modeling

In the proposed framework of the day-ahead EV and HP energy planning, the operators are assumed to be economically rational. Therefore, their objective is to minimize the energy cost of the EV and HP energy consumption in the day-ahead market as Eqn.5.41 with the constraints of the energy requirements of EVs and HPs.

$$\min_{x_t} \sum_{t \in T} \alpha_t x_t \tag{5.41}$$

where α_t is the spot price of electricity at time t in the day-ahead market; x_t is the energy consumption of the EV or HP at time t.

Specifically, the energy plans of the EV and HP operators in the day-ahead can be determined by the optimal solutions based on the electricity pricing. For EVs, the energy plans can be defined as the solution of the EV operator's own optimization as follows. For all $v \in V$,

$$\min_{x_{v,t}} \sum_{t \in T} \alpha_t x_{v,t} \tag{5.42}$$

Subject to

$$e_v^- \leqslant \sum_{\tau=0}^{t} (x_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall t \in T \tag{5.43}$$

$$x_{v,t} \leqslant p^+ s_{v,t} \quad \forall t \in T \tag{5.44}$$

$$x_{v,t} \geqslant 0 \quad \forall t \in T \tag{5.45}$$

where $x_{v,t}$ is the charging energy of vehicle v at time t; $d_{v,t}$ is the driving energy consumption of vehicle v at time t; e_v^- is the lower limit of the SOC level of vehicle v; e_v^+ is the upper limit of the SOC level of vehicle v; e_v^0 is the SOC level of vehicle v; p^+ is the upper power limit of the EV charging; $s_{v,t}$ is the charging availability indicator of vehicle v at time t; V is the set of EVs in the grid; T is the set of time intervals for the planning.

For HPs, the energy plans can be defined as the solution of the HP operator's own optimization as follows. For all $h \in H$,

$$\min_{x_{h,t}} \sum_{t \in T} \alpha_t x_{h,t} \tag{5.46}$$

Subject to

$$T_{in}^{-} \leqslant T_{in,h,t} \leqslant T_{in}^{+} \quad \forall t \in T \tag{5.47}$$

$$Q_{h,t} \leqslant Q_h^{+} \quad \forall t \in T \tag{5.48}$$

$$Q_{h,t} = x_{h,t} COP_h \quad \forall t \in T \tag{5.49}$$

$$x_{h,t} \geqslant 0 \quad \forall t \in T \tag{5.50}$$

where $x_{h,t}$ is the electrical demand of the HP h at time t; $T_{in,h,t}$ is the temperature of the house interior of HP h; T_{in}^{-} and T_{in}^{+} is the lower and upper temperature limits of the house interior; $Q_{h,t}$ is the heat output of the HP h at time t; Q_h^{+} is the heat output limit of HP h; COP_h is the coefficient of performance of HP h; H is the set of the HPs in the grid.

When there is a considerable number of EVs and HPs in the power system, their demand is comparable to the conventional demand and it will inevitably influence the electricity spot prices in the day-ahead market. As a result, the spot prices can be formulated as a function of the conventional demand and the flexible demand from EVs and HPs as illustrated in Eqn.5.51.

$$\alpha_t = f_{sp}\left(D_t + \sum_{v \in V} x_{v,t} + \sum_{h \in H} x_{h,t}\right) \tag{5.51}$$

where D_t is the conventional demand in the grid at time t; f_{sp} is the function of electricity spot prices to the demand in the day-ahead market.

The energy planning of the EV and HP operators formed a non-cooperative game in the day-ahead market. The operators are the players and their energy plans are their strategies. Therefore, the strategy of an EV and HP operator can be expressed as follows.

$$s_v = \{x_{v,t} : t \in T\}$$

$$s_h = \{x_{h,t} : t \in T\}$$

where s_v is the strategy of an EV operator; s_h is the strategy of a HP operator.

The operators, as the players in the game, have the payoff functions as Eqn.5.52 and Eqn.5.53 according to the formulation from Eqn.5.42 to Eqn.5.50 and the notations mentioned above. All the operators act optimally to maximize their payoff functions considering the other operators' actions in the day-ahead market.

$$\begin{aligned} f_v(s) &= -\sum_{t\in T} \alpha_t x_{v,t} \\ &= -\sum_{t\in T} f_{sp}\left(D_t + \sum_{v'\in V} x_{v',t} + \sum_{h'\in H} x_{h',t}\right) x_{v,t} \\ &= \widetilde{f_v}\left(s_v, \sum_{v'\in V} s_{v'} + \sum_{h'\in H} s_{h'}\right) \end{aligned} \tag{5.52}$$

$$\begin{aligned} f_h(s) &= -\sum_{t\in T} \alpha_t x_{h,t} \\ &= -\sum_{t\in T} f_{sp}\left(D_t + \sum_{v'\in V} x_{v',t} + \sum_{h'\in H} x_{h',t}\right) x_{h,t} \\ &= \widetilde{f_h}\left(s_h, \sum_{v'\in V} s_{v'} + \sum_{h'\in H} s_{h'}\right) \end{aligned} \tag{5.53}$$

where s is the strategies of all the operators; f_v is the payoff function of EV operator v on the strategies of all the operators; $\widetilde{f_v}$ is the payoff function of EV operator v on its own strategy and the aggregate strategies of all the operators; f_h is the payoff function of HP operator h on the strategies of all the operators; $\widetilde{f_h}$ is the payoff function of HP operator h on its own strategy and the aggregate strategies of all the operators.

In this game of the operators, their actions or strategies are only coupled through the payoff functions. As shown in Eqn.5.52 and Eqn.5.53, the payoff functions of the operators depend only on their own strategies and the aggregate strategies of all the operators. Therefore, the game of the operators in the day-ahead market is an aggregative game. When the number of the EVs and HPs in the market is large enough, the actions of the operators can be viewed as independent on the actions of any other individual operator but the collective behaviors of all the EV and HP operators as the term $\sum_{v'\in V} x_{v',t} + \sum_{h'\in H} x_{h',t}$ in Eqn.5.52 and Eqn.5.53.

As mentioned earlier in this section, the electrical demand have impact on the spot prices in the day-ahead market. Fig.5.3 shows the electrical demand and the spot prices of electricity in the day-ahead market in Denmark in 2014.

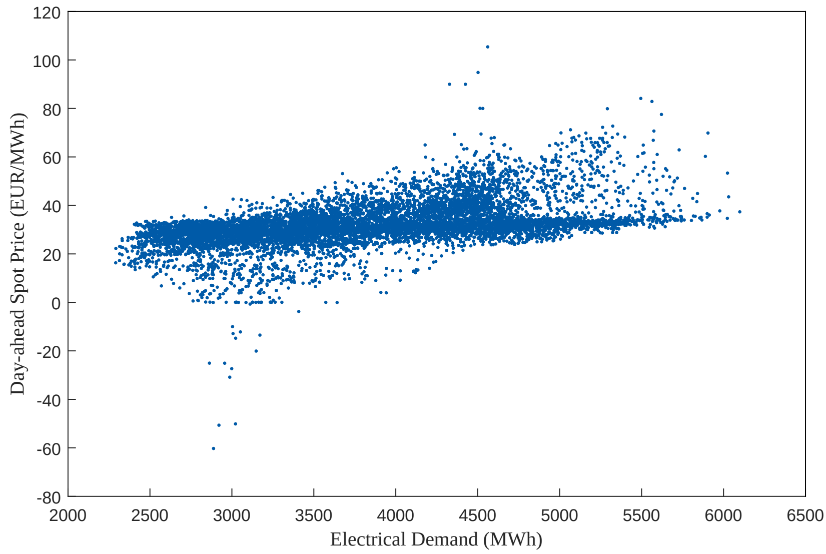


Figure 5.3: Day-ahead Electricity Spot Price on the Electrical Demand in Denmark

Due to the volatility of the spot price in the day-ahead market, the day-ahead spot price of electricity can be modeled by a linear function of the electrical demand with a random walk process [85]. Therefore, the expectation of the electricity spot prices in the day-ahead market can be approximated by a linear function of the demand. Without loss of generality, it is assumed that the function of the electricity spot price in the day-ahead market on the electrical demand is as Eqn.5.54 in this study. However, the study on the game model in this study can also be applied with other functions as long as the functions show a relation that the price rises up when the demand increases as the common sense.

$$\alpha_t = \alpha_t^0 + \beta \left(\sum_{v \in V} x_{v,t} + \sum_{h \in H} x_{h,t} \right) \tag{5.54}$$

where α_t^0 is the predicted baseline spot price according to the conventional demand at time t; β is the coefficient of spot price on the electrical demand.

The coefficient β is the derivative of the electricity spot price over the load. It can be calculated from the historical data of the load and price in the spot market with the following equation [86].

$$\beta = \frac{\mathrm{d}\alpha}{\mathrm{d}x} = \frac{1}{N_t} \sum_{t=1}^{N_t} \frac{\alpha_t - \alpha_{t-1}}{x_t - x_{t-1}} \tag{5.55}$$

where α is the electricity spot price; x is the electricity load; α_t is the historical electricity spot price at time t; x_t is the historical electricity load at time t; N_t is the set of the time series of the historical data.

Thus, the payoff functions of the EV and HP operators in Eqn.5.52 and Eqn.5.53 can be expressed alternatively as Eqn.5.56 and Eqn.5.57 respectively.

$$f_v(s) = -\sum_{t \in T} \alpha_t x_{v,t} = -\sum_{t \in T} \left[\alpha_t^0 + \beta \left(\sum_{v' \in V} x_{v',t} + \sum_{h' \in H} x_{h',t} \right) \right] x_{v,t} \tag{5.56}$$

$$f_h(s) = -\sum_{t \in T} \alpha_t x_{h,t} = -\sum_{t \in T} \left[\alpha_t^0 + \beta \left(\sum_{v' \in V} x_{v',t} + \sum_{h' \in H} x_{h',t} \right) \right] x_{h,t} \tag{5.57}$$

As shown in Eqn.5.56 and Eqn.5.57, the payoffs of the EV and HP operators are determined by the price of the electricity, which will be influenced by the collective actions of all the operators. An iteration process is carried out to indicate the interactions between the EV and HP operators' actions and electricity spot prices with such payoff functions. A case with 100% EV penetration and 31% HP penetration (all the residential heating which is not supplied by either District Heating or sustainable resources currently) in Denmark is assumed in the process. In each iteration, the electricity spot prices α_t are updated by the demand of EVs and HPs as Eqn.5.54 in the last iteration. Then the EV and HP operators carry out the energy planning according to the updated prices with the optimization model with Eqn.5.42 to 5.45 and Eqn.5.46 to 5.50 respectively. The base spot prices α_t^0 in the iterations are as shown in Appendix B.

Fig.5.4 shows the energy planning of the EV and HP operators in the first three iterations. Fig.5.5 shows the corresponding electricity spot prices in the day-ahead market with the demand of EVs and HPs in the first three iterations.

In the first iteration, the EV and HP operators carry out their energy planning according to the base prices. Thus, the demand of EVs and HPs congregates at the hours when the spot prices are the lowest of the day. Such high demand results in the high spot prices at the corresponding hours according to Eqn.5.54.

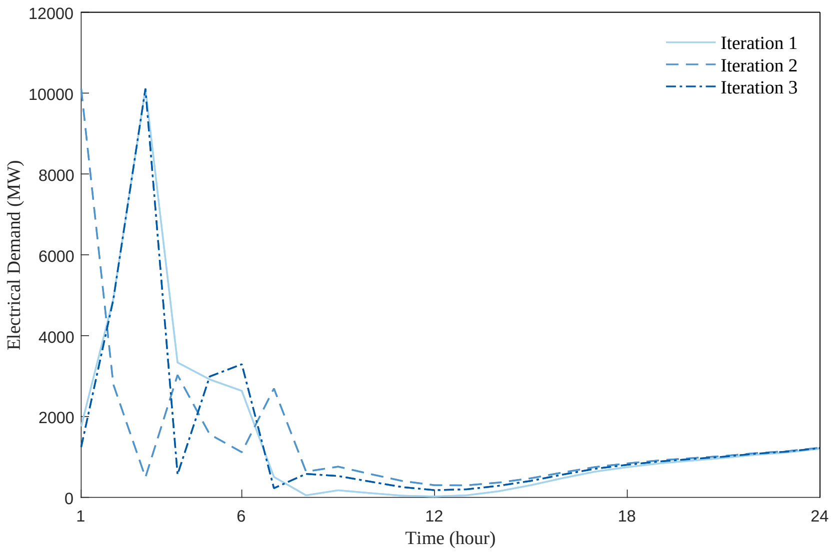


Figure 5.4: Electrical Demand of EVs and HPs in the First Three Iterations

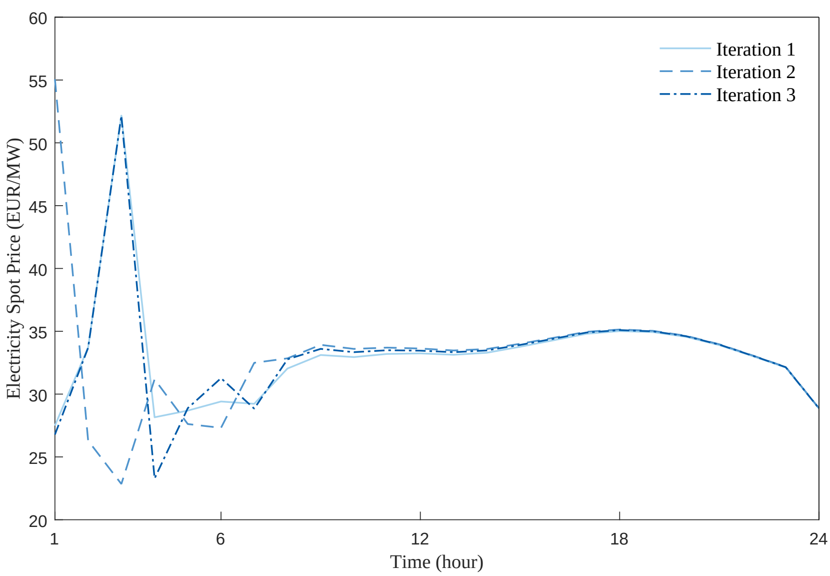


Figure 5.5: Electricity Spot Prices in the First Three Iterations

Consequently, in the second iteration, the EV and HP operators shift the demand from the peak hours in the first iteration and allocate the demand at the hours with the lowest updated spot prices. Similar to the first iteration, the congregated demand in the second iteration boosts the spot prices at the corresponding hours. Therefore, in the third iteration, the EV and HP operators shift the demand of the EVs and HPs again to avoid the high spot prices in the second iteration. The demand curve in the third iteration shares a similar peak with the case in the first iteration. In this way, the demand of EVs and HPs moves back and forth during the iterations.

The results of the iterations indicate the relations between the operators actions and the electricity spot price. The operators shift the EV and HP demand to the low-spot-price period in order to minimize the energy cost and meanwhile the demand increases the electricity spot prices at the same period. However, with the linear objective functions as Eqn.5.42 and 5.46 in the optimizations of the EV and HP operators, the iteration process does not converge. The EV and HP demand shifts the same way as shown in Fig.5.4 during the iterations without reaching a better solution. More importantly, the equilibrium of the aggregative game between the EV and HP operators can not be reached. Due to the linear objective functions in the operators' optimizations, all the operators allocates the demand at a short period and boosts the spot prices sharply at the corresponding hours. As a result, the solution of any iteration is not optimal for the EV and HP operators whose objective is to minimize the cost of the energy consumption. Given the collective behaviors of all the operators, the operators changes their own strategies in each iteration and the equilibrium can not be obtained with the linear formulations.

In order to address the issues with the linear objective functions in the iteration process and reach the optimal solutions of operators for the the EV and HP energy planning, a quadratic model is built in the optimizations of the EV and HP operators in the iteration process. The model serves the purpose that the optimal solution for each EV and HP operator can be reached given the collective behaviors of all the operators in the aggregative game, and consequently the equilibrium can be obtained. Meanwhile, no extra cost for the EV and HP aggregators compared to the reality should be introduced in the model. The quadratic model is introduced as follows.

For the EV operators, the optimization in the ith iteration is as shown in Eqn.5.58 to 5.61.

$$\min_{x_{v,t}} \sum_{t \in T} \left[\alpha_t x_{v,t} + \delta (x_{v,t} - x_{v,t}^{(i-1)})^2 \right] \tag{5.58}$$

Subject to

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall t \in T \tag{5.59}$$

$$x_{v,t} \leqslant p^+ s_{v,t} \quad \forall t \in T \tag{5.60}$$

$$x_{v,t} \geqslant 0 \quad \forall t \in T \tag{5.61}$$

where δ is a tracking parameter with a positive constant value; $x_{v,t}^{(i-1)}$ is the solution of the optimization of the EV operator in the $(i-1)$th iteration.

Similarly, the optimization for the HP operators in the ith iteration is as shown in Eqn.5.62 to 5.66.

$$\min_{x_{h,t}} \sum_{t \in T} \left[\alpha_t x_{h,t} + \delta(x_{h,t} - x_{h,t}^{(i-1)})^2\right] \tag{5.62}$$

Subject to

$$T_{in}^- \leqslant T_{in,h,t} \leqslant T_{in}^+ \quad \forall t \in T \tag{5.63}$$

$$Q_{h,t} \leqslant Q_h^+ \quad \forall t \in T \tag{5.64}$$

$$Q_{h,t} = x_{h,t} COP_h \quad \forall t \in T \tag{5.65}$$

$$x_{h,t} \geqslant 0 \quad \forall t \in T \tag{5.66}$$

where $x_{h,t}^{(i-1)}$ is the solution of the optimization of the HP operator in the $(i-1)$th iteration.

In the ith iteration, the electricity spot price α_t is updated with the solutions in the $(i-1)$th iteration according to the relation of demand and spot price. Without loss of generality, we apply the demand and spot price function as Eqn.5.54 in this study. Therefore, the spot price α_t in the ith iteration is calculated as follows in Eqn.5.67.

$$\alpha_t = \alpha_t^0 + \beta \left(\sum_{v \in V} x_{v,t}^{(i-1)} + \sum_{h \in H} x_{h,t}^{(i-1)} \right) \tag{5.67}$$

The major process of the iterations is as shown in the flow chart in Fig.5.6.

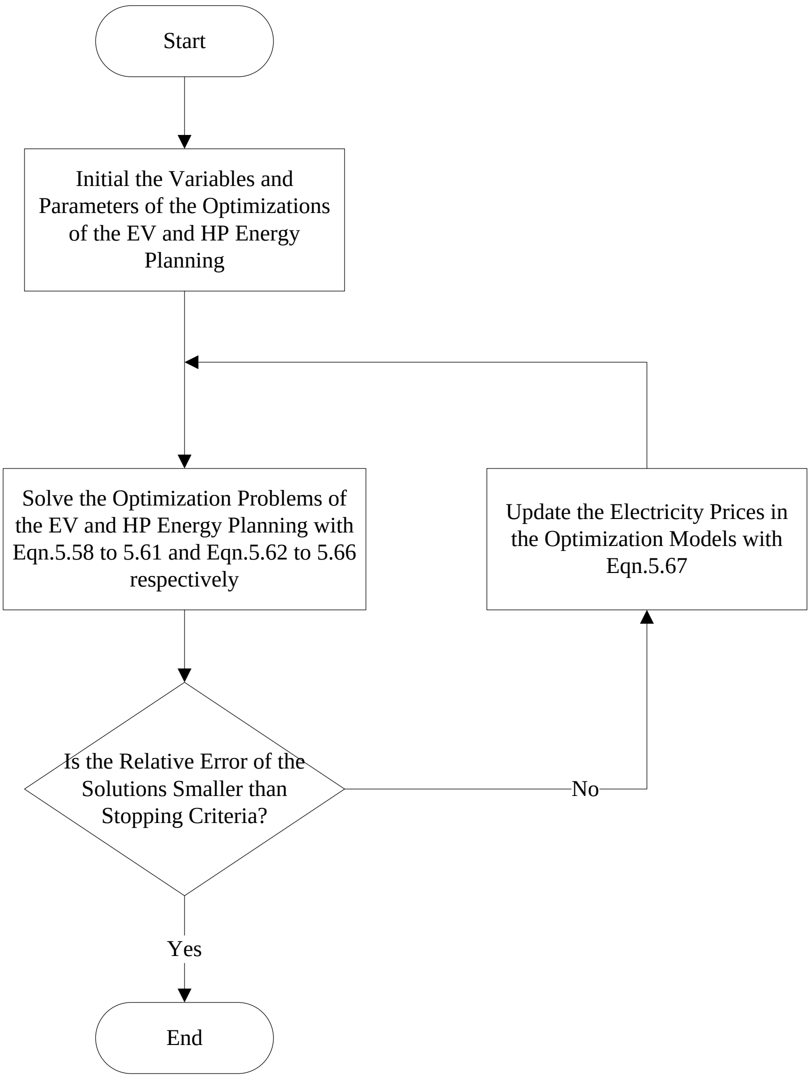


Figure 5.6: Main Steps of the Iteration Process with the Quadratic Programming

As shown in Eqn.5.58 and 5.62, a quadratic term is added in the objective function of the operator's optimization in the iterations. The quadratic term is with a small positive coefficient δ. It introduces a tracking cost in the objective function for preventing the strategies of the operators from shifting arbitrarily as the case with the linear objective function. When the iteration converges, the differences between the solutions in the two neighbouring iterations should be small enough and within the stopping criteria of the iteration process. The quadratic term in the objective function Eqn.5.58 and 5.62 is small enough and can therefore be neglected in this case. Further, the electricity spot price α_t updated with the solutions of the previous iteration is close enough to the price calculated with the solutions in the current iteration. Consequently, there is no extra cost added to the optimal solutions of the EV and HP operators compared to the linear optimization model with the objective functions as Eqn.5.42 and 5.46 which reflect the real cost of the operators in practice. The electricity spot price α_t used in the final iteration can be considered the same as the price with the optimal solutions neglecting the small difference between the last two iterations multiplied by the coefficient β. Thus, the solution through the iteration process with the quadratic model can be considered the same as the optimal solution with the electricity spot prices when the EV and HP demand in the grid is as the solution itself. The optimal solution of the EV and HP operators is guaranteed given the collective behaviors of all the operators, and equilibrium of the aggregative game is reached.

As the parameter δ is positive, the optimization model is strictly convex and therefore a unique optimal solution is guaranteed given that the constraints can be satisfied. The optimization is a standard quadratic optimization model. It can be solved by a number of commercial solvers efficiently [87].

5.3.3 Numerical Case Studies

In order to illustrate the performance of the iteration model with the quadratic optimizations, a case study is carried out. The details and results of the case study are presented in this section.

5.3.3.1 Scenario Descriptions

In the case study, a 100% EV penetration level in Denmark is assumed. Currently, about 69% of the residential heating demand in Denmark is supplied by district heating or sustainable resources. All the rest of the residential heating is assumed to be provided by HPs in the case study. The EV number in the case study is 2.1×10^6, the HP number in the case study is 8.0×10^5.

The driving patterns of the EVs in the study are obtained from the Denmark National Travel Surveys as described in Section 3. The EV parameters are as described in Section 5.1.3. The thermal dynamic of the houses is modeled according to Eqn.5.31 and 5.32. The environmental weather parameters are as the Denmark profiles described in Section 4.2.2.2. The interior temperature preference is set in the range 20-24°C. The COP of the HPs is set to be 3.1375. The sizes of the houses are uniformly random from 40 to 250m^2. The capacity of the heat pumps is set according to the size of the houses. For the houses with an area less than 90m^2, the capacity of the heat pump is set to be 5kW; for the houses with an area between 90 to 150m^2, the capacity of the heat pump is set to be 10kW; for the houses with an area over 150m^2, the capacity of the heat pump is set to be 15kW.

The predicted baseline spot price with the conventional demand α_t^0 is assumed as shown in Appendix B. The historical data in the day-ahead market of Denmark is studied. The coefficient of spot price on the electrical demand β is calculated with the historical data according to Eqn.5.55. It takes the value of 0.0036EUR/MW in the case study accordingly.

5.3.3.2 Case Study Results

The demand of the EVs and HPs with the aggregative game model in the case study is as shown in Fig.5.7.

In the case study, the EVs and HPs consume more at night when the baseline spot prices are low as the conventional demand is expected to be low in the period. The flexible demand of EVs and HPs drops during the day when the baseline spot prices increase for lower energy consumption cost. However, unlike the case with the linear optimization, the EV and HP demand does not congregate at one or two hours and prevents the peak spot prices at the corresponding hours. With the quadratic optimization model in the iterations, the majority of the EV and HP demand at night spreads out into a few hours.

The expected electricity spot prices in the day-ahead market with the flexible demand of EVs and HPs in the case study is as shown in Fig.5.8.

Fig.5.8 shows both the baseline prices only with the conventional demand and the expected electricity spot prices with the flexible demand of EVs and HPs in the day-ahead market. Due to the EV and HP demand, the spot prices

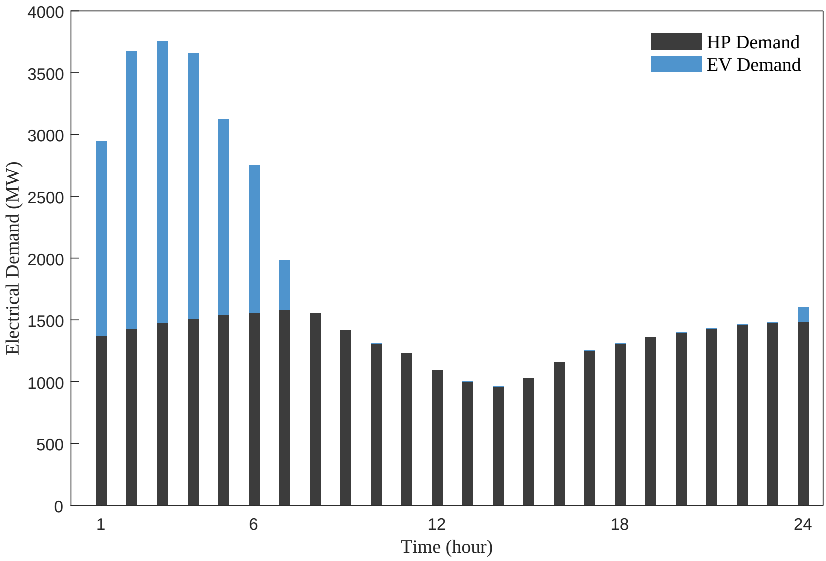


Figure 5.7: Electrical Demand of EVs and HPs in the Case Study

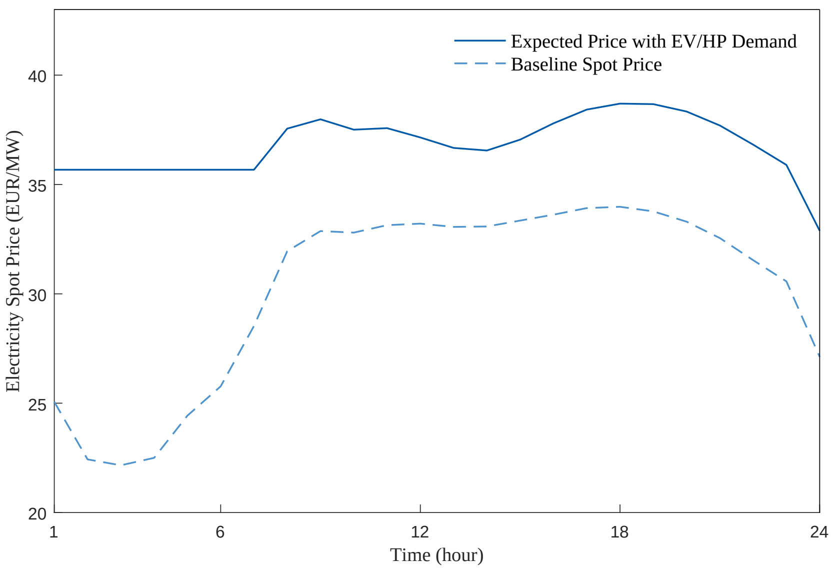


Figure 5.8: Expected Electricity Spot Prices in the Day-ahead Market in the Case Study

increase the most when the baseline prices are low. It is because of the fact that the objective of the EV and HP operators is to minimize their own energy consumption cost. Therefore, they tend to consume more when the baseline prices are low at night as indicated in Fig.5.7. However, the flexible demand of EVs and HPs does not congregate at one or two hours as the case with linear optimization model in order to prevent generating high spot prices at the time which will eventually lead to a high energy cost. The high demand period at night spreads out into a few hours and forms flat spot prices in the period. Such flat spot prices result from the optimal solutions for a minimal energy cost of the operators. When there is a time interval with a lower spot price, the demand will be shifted to the moment by the operators for a lower cost. Consequently, the flexible demand of EVs and HPs is filled in the moment when the spot price is low by the operators and flatten the prices in the period.

The stopping criteria for the iteration process is based on the error of the optimization solutions in the iterations. It is evaluated by the mean absolute relative error between the two neighbouring iterations as follows.

$$ARE_j = \frac{\sum_{t \in N_t} \left| x_{j,t}^{(i)} - x_{j,t}^{(i-1)} \right|}{\frac{1}{T} \sum_{t \in T} x_{j,t}^{(i)}} \quad \forall j \in H \cup V \tag{5.68}$$

$$MARE = \frac{1}{N_{hv}} \sum_{j \in H \cup V} ARE_j \tag{5.69}$$

where ARE_j is the absolute relative error of the energy plan solution of EV/HP j in the iterations; $x_{j,t}^{(i)}$ is the solution of the EV and HP energy plan in the ith iteration; T is the set of time intervals of the energy planning; N_t is the cardinality of the set T; H is the set of the HPs in the grid; V is the set of the EVs in the grid; $MARE$ is the mean absolute relative error of the energy plan solutions of the EVs and HPs in the iterations; N_{hv} is the cardinality of the set $H \cup V$.

The mean absolute relative error of the iteration process is as shown in Fig.5.9.

As shown in the figure, the iteration process converges quickly with the quadratic optimization model. In the case study, the mean absolute relative error of the iteration process drops sharply in the first five iterations. The mean absolute relative error is less than 2.5×10^{-4} after the 25th iteration in the case study.

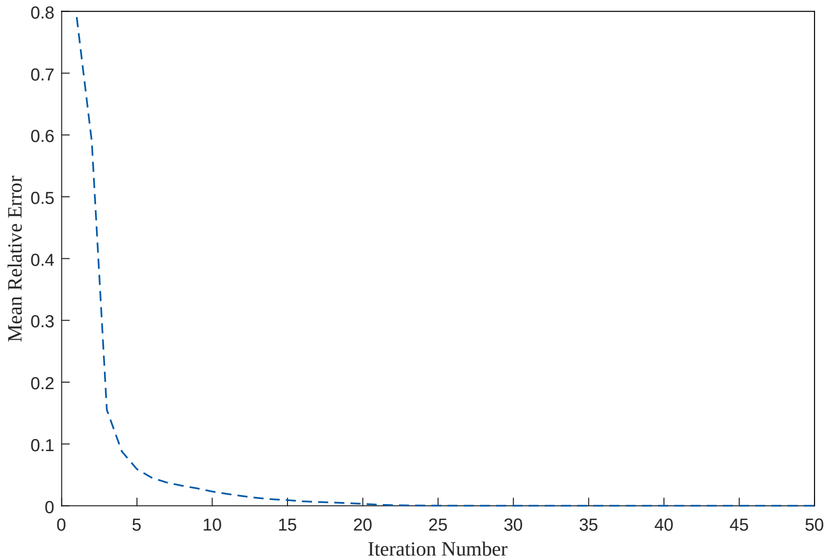


Figure 5.9: Mean Absolute Relative Error in the Iterations of the Case Study

Chapter 6

Providing Ancillary Services from EVs and HPs

In the Nordic region, the large scale deployment of EVs and HPs is considered not only as an efficient method to limit the GHG emission and fossil fuel consumption in the transportation and heating sectors but also as a potential approach to cope with the intermittency due to the further utilization of RES in the Nordic region. With increasing amounts of RES in the Nordic power system, more reserves will be needed by the grid due to the inherent uncertainties of RES. Therefore, the flexible demand of EVs and HPs will play a more important role in the future power system of the Nordic region by providing extra reserves to the grid.

The study in this section aims to investigate the capability of EVs and HPs for providing ancillary services in the Nordic power system. The combined modeling of the EV and HP energy planning is proposed for both the ancillary services provision decisions and their own consumption considering the detailed driving and heating requirements. Furthermore, the impacts of the EV and HP enengy planning on the electricity spot market are also considered in the proposed model.

6.1 Preliminary

The flexible demand in the power system is viewed as a potential source of extra ancillary services for the grid and it has drawn a lot of research attention. A number of studies focusing on the topic regarding EVs to provide ancillary services to the grid have been carried out in recent years. The work in [88–94] evaluates the economical opportunities for the V2G enabled EVs to realize revenues from the regulation service market. The technical possibility of EVs to contribute to primary frequency regulations is discussed in [95] while the work in [96] focuses on the possibilities of plug-in vehicles to produce ancillary services for distribution networks. The work in [97] discusses and estimates the ancillary services potential of EVs in the German power system. A contract-based mechanism is presented in [98, 99] for the aggregators to provide incentives for EVs to participate in ancillary services to grid. The work in [100] proposes the framework with the VPP technology for EVs to schedule their charging and provide multiple ancillary services to the network. The work in [101] also develops an integrated decision making framework for the planning and real-time control decisions of the demand providing ancillary services to the wholesale market. The controllable demand of EVs is one of the targets in this study. An EV intelligent energy management system framework for frequency regulation application is proposed in [102]. It offers a perspective about the integration of different resources that could advance the implementation of V2G programs for frequency regulation applications. A distributed EV coordination mechanism is proposed in [103] to enable the management of the operation of an EV fleet to offer V2G regulation services for system support operations. The work in [104] carries out the tests on 15 EVs providing upward and downward regulations to the grid to compare the decentralized and centralized mechanisms at the University of Delaware. The work in [105] proposes a robust EV frequency regulation algorithm to determine the hourly regulation capacity for the EV considering the randomness of the automatic generation control signal under a performance-based compensation paradigm in the North American context. The work in [106] investigates the potential of unidirectional EV charging to provide cost benefits and regulation services to the grid with proper power-draw scheduling and dynamic pricing. The work in [107–109] develops an optimal combined bidding formulation for regulation and spinning reserves of the EVs. It is based on a unidirectional V2G framework and the reserves are supposed to be provided by varying the EV charging from the preferred operating points (POPs). The work in [110–112] proposes an optimal bidding of ancillary services by EVs in different markets including regulation and spinning reserves. The electricity market uncertainties are considered using fuzzy linear optimization in the study. The work in [113–115] presents the optimization models for the decisions on battery charging and providing ancillary services. Decentralized and centralized V2G control methods are proposed for EVs to participate in primary and supplementary frequency regulations considering the EV charging demand in the work of [116, 117]. The work in [118, 119] describes the EV aggregation framework and formulates the optimization model of the EVs to participate in the day-ahead and the ancillary reserve markets. A multi-level architecture for bidirectional V2G regulation service is proposed in [120, 121] to provide frequency regulation service to the utility grid under the coordination of the aggregators. The work in [122] models the EVs as reactive power service providers in the distribution system. The availability of EVs to supply the voltage regulation in the distribution system is investigated in [123, 124]. The work in [125] also proposes a decentralized optimization methodology to coordinate the EV charging for the voltage regulation in the distribution system. The work in [126] analyzes the potential voltage support functions from EVs and photovoltaic installations (PVs) in a low voltage distribution network. The work in [127] investigates the concurrent provision of local and system wide services from EVs in the low voltage network with high penetration of PVs. It analyzes the potential of reactive power control from EVs with focus on overvoltages caused by providing frequency regulation coincides with high PV production. The work in [128] examines the possibility of bi-direction power flow control capability of EV charging stations in providing the voltage support for distribution network operations to improve the fault-ride-through of adjacent wind turbines. The work in [129] analyzes power balancing support services from EVs and the feasible levels of EV integration possible to provide regulations on typical wind dominated networks in Denmark. The work in [130] presents several control approaches for the charging and discharging of the EV batteries to reduce power imbalances in the grid.

On the other hand, the research on HPs to provide ancillary services to the power system is limited compared to EVs. The work in [131] introduces the concept of a real-time market and information architecture of a smart grid framework to utilize numerous small end-users including HPs to offer the grid additional balancing and ancillary services. The economic exploitation of flexible thermal loads to provide tertiary frequency control reserves is evaluated in [132] with a simulation of 5000 HPs.

Previous work covers a variety of aspects of the ancillary services provision from the flexible demand, especially for EVs. However, a detailed modeling of the energy planning and ancillary services provision decisions for both EVs and HPs considering the detailed driving and heating requirements in the Nordic region is missing at present. Furthermore, the impacts of the EVs and HPs on the day-ahead spot market in their energy plans for providing the ancillary services are not considered in previous work. This study aims to investigate the capability of EVs and HPs to provide ancillary services to the grid in the Nordic region. The combined modeling of the EV and HP energy planning for both their own consumption and the ancillary services provision decisions is proposed. The detailed driving and heating requirements of the EVs and HPs as well as the impacts of the demand of EVs and HPs on the electricity spot market are considered in the study.

Among the ancillary services in the power system, frequency regulation is with the highest value [133]. Further, the primary frequency reserve is the most valuable frequency regulation due to its high response requirement. Therefore, we focus on the investigation of the possibility and capacity of EVs and HPs to provide primary frequency reserves to the grid in the Nordic region in this study.

The study in [134] has shown that the household flexible demand is suitable to serve as frequency controlled reserved. Further, studies have shown that EVs can response to the trigger signals of the frequency reserve within the requirements of the grid regulations using current infrastructures and technologies [133, 135]. In this study, it is assumed that the EV and HP facilities can respond to the reserve requirements properly according to the code of the grid in the Nordic region.

6.2 Frequency Reserve in the Nordic Power System

This study focuses on the frequency-controlled normal operation reserve (FNR) which is the primary frequency reserve in the Nordic region. Without loss of generality, the technical requirements of the reserve from the independent system operator (ISO) in DK2 region of Denmark (Eastern Denmark) is adopted in this study. The key requirements are as shown in Tab.6.1 [136].

Table 6.1: Technical Requirements for the Frequency-Controlled Normal Operation Reserve in DK2 Region

	Frequency-controlled normal operation reserve
Activation Time	150s
Frequency Range	49.9-50.1Hz
Activated Capacity	Linearly at frequency deviations
Duration	Continuously
Procurement	Daily auctions one/two day ahead
Regulation Type	Symmetrical
Energy Price	Regulating power price

In DK2 region of Denmark, the frequency-controlled normal operation reserve is supplied at a frequency deviation of up to +/- 100mHz relative to the reference frequency of 50Hz. The reserve is considered to be maintained continuously and purchased as a symmetrical product. Therefore, the reserve suppliers must provide both upward regulating power (in case of under-frequency) and downward regulating power (in case of over-frequency). The reserves are contracted capacity on an hourly basis and supplied linearly at the frequency deviation in the 49.9-50.1Hz range. Therefore, the hourly activated reserves depends on the system frequency deviation to 50Hz and the contracted reserve capacity.

Regulation takes place during all hours of the day and not necessarily during the time of peak demand [133]. It is also the case for the frequency reserve in the Nordic region. An example of the system frequency in the Nordic power system in a month is shown in Fig.6.1. The data are obtained from the recorded data from a 60kV network in the Nordic region in September 2014.

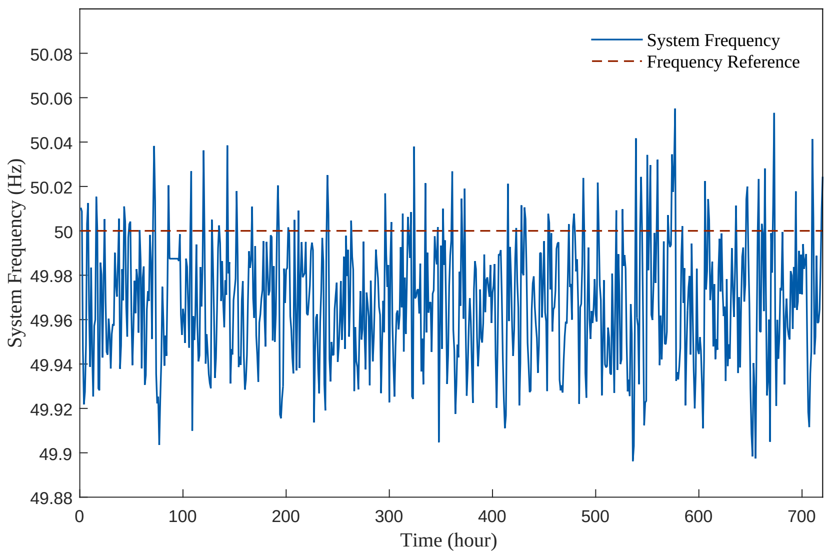


Figure 6.1: System Frequency in the Nordic Region

As the frequency reserves are supplied linearly at the frequency deviation, the activated frequency-controlled normal operation reserves over the reserve capacity can be determined according to the frequency of the system. For example, the activated frequency-controlled normal operation reserves for the case in Fig.6.1 is as shown in Fig.6.2.

Fig.6.2 shows the activated reserve coefficient for the case, which is the activated

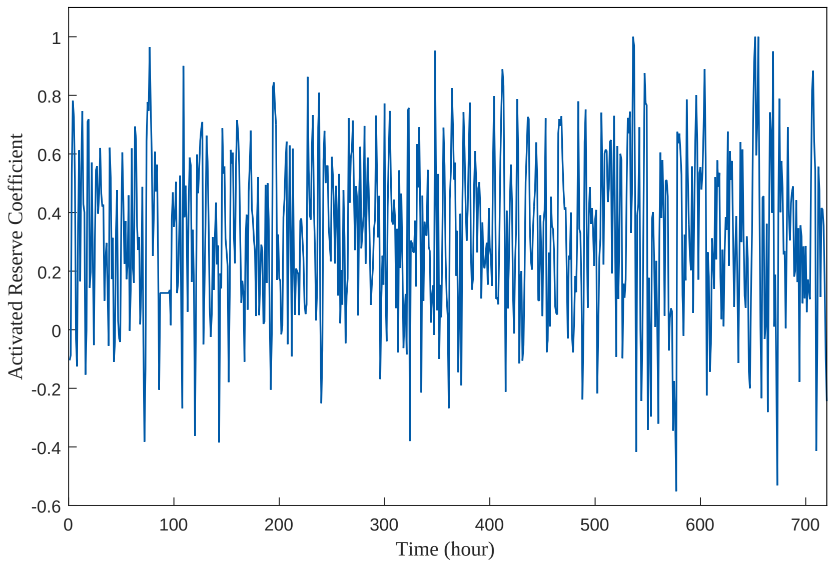


Figure 6.2: Activated Frequency-Controlled Normal Operation Reserves in the Nordic Region

reserve over the reserve supply capacity. Positive values in the figure refer to upward regulations and negative values refer to downward regulations. As mentioned before, the frequency reserves are supplied linearly at the frequency deviation in the 49.9-50.1Hz range. The activated reserve coefficient can be determined as follows.

$$\varphi_t = \begin{Bmatrix} -1, & f_t > 50.1 \\ \dfrac{50 - f_t}{0.1}, & 49.9 \leqslant f_t \leqslant 50.1 \\ 1, & f_t < 49.9 \end{Bmatrix} \quad \forall t \in T \tag{6.1}$$

where φ_t is the activated reserve coefficient at time t; f_t is the system frequency in Hz at time t.

As discussed above, the activated frequency reserve is dependent on the system frequency. The frequency of the system in the Nordic region is studied from September 2014 to August 2015. The corresponding activated frequency-controlled normal operation reserve coefficients along the day are shown in Fig.6.3.

The distribution of the activated frequency-controlled normal operation reserves is as shown in Fig.6.4. As shown in the figure, the activated frequency controlled

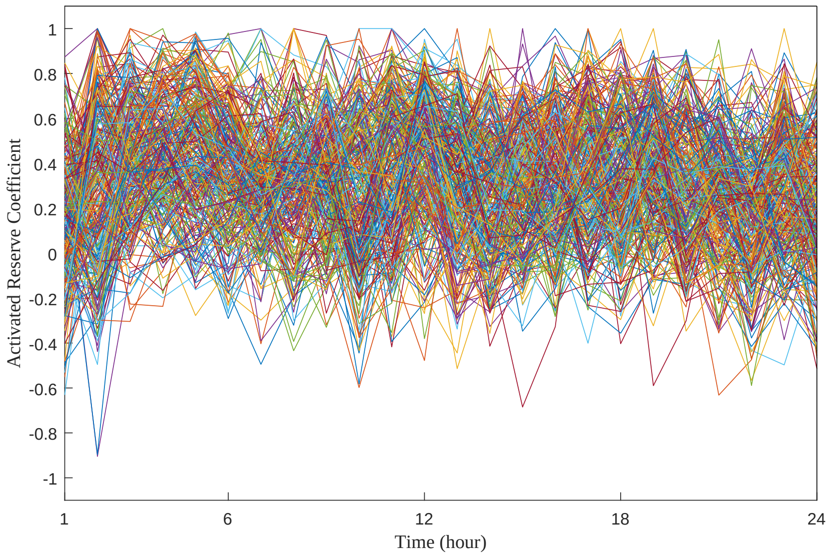


Figure 6.3: Activated Frequency-Controlled Normal Operation Reserves along the Day

reserves do not balance on both ways of the regulations. Instead, the upward regulations are activated more often in the Nordic power system. In most of the cases, the frequency controlled reserves are activated for upward regulations with a small coefficient. The probability decreases gradually in either directions when the activated ratio goes up for upward regulations or the downward regulations are activated. It is rare the case when the downward regulations are activated with a full reserve capacity. The expectation of the activated frequency-controlled normal operation reserve coefficient is 0.324 according the distribution of the activated reserves as shown in the figure.

6.3 Mathematical Modeling

In this section, the detailed mathematical models of the EVs and HPs to provide frequency-controlled reserves are introduced. For the EV and HP scheduling, the operators need to submit both the bids for the electricity consumption to the day-ahead spot market and the bids for frequency reserve provision to the frequency reserve auction the day before in the Nordic region. Therefore, the EV and HP operators need to determine both the energy plans and the frequency reserve capacity offers one day ahead. For EVs, the detailed mathematical model

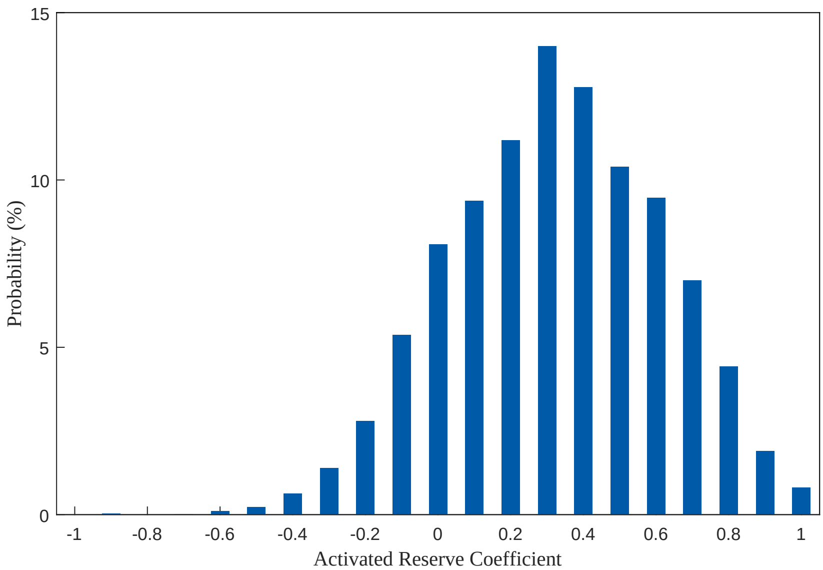


Figure 6.4: Activated Frequency-Controlled Normal Operation Reserves Distribution

for the day-ahead planning is as follows.

$$\min_{x_{v,t}} \sum_{t \in T} (\alpha_{s,t} x_{v,t} - \alpha_{f,t} y_{v,t} - \alpha_{r,t} E\left[\varphi_t y_{v,t}\right]) \tag{6.2}$$

Subject to

$$e_v^- \leqslant \sum_{\tau=0}^{t} (x_{v,\tau} - \varphi_\tau y_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall \varphi_t \in \Phi, \forall t \in T \tag{6.3}$$

$$x_{v,t} + y_{v,t} \leqslant p^+ s_{v,t} \quad \forall t \in T \tag{6.4}$$

$$x_{v,t} - y_{v,t} \geqslant 0 \quad \forall t \in T \tag{6.5}$$

$$y_{v,t} = s_{v,t} \varrho_v \psi_t \quad \forall t \in T \tag{6.6}$$

$$x_{v,t} \geqslant 0 \quad \forall t \in T \tag{6.7}$$

$$y_{v,t} \geqslant 0 \quad \forall t \in T \tag{6.8}$$

where $x_{v,t}$ is the energy purchased for vehicle v at time t in the day-ahead electricity spot market; $\alpha_{s,t}$ is the electricity spot price at time t in the day-ahead electricity spot market; $y_{v,t}$ is the frequency reserve capacity provided by vehicle v at time t; $\alpha_{f,t}$ is the price for the frequency-controlled normal operation reserve at time t; $\alpha_{r,t}$ is the regulating power price at time t; φ_t is the activated frequency reserve coefficient at time t; $d_{v,t}$ is the driving energy consumption of vehicle v at time t; e_v^- is the lower limit of the SOC level of vehicle v; e_v^+ is the upper limit of the SOC level of vehicle v; e_v^0 is the SOC level of vehicle v; p^+ is the upper power limit of the EV charging; $s_{v,t}$ is the charging availability indicator of vehicle v at time t; ϱ_v is the frequency reserve provision coefficient of vehicle v to the reserve requirements of the grid; ψ_t is the expected frequency reserve requirements of the grid at time t; Φ is the set of possible activated reserve coefficients; T is the set of time intervals for the planning.

The EV operators, which are assumed to be economically rational, have an objective to maximize their own surplus in the day-ahead electricity spot market and the frequency reserve auctions. Therefore, the objective function is as Eqn.6.2 minimizing the charging cost minus the avenue of the frequency reserves provided by the EV and the energy compensation of the activated reserves with regulating power prices subject to the SOC limit constraint 6.3, the EV charging energy limit constraint 6.4, the charging energy non-negativity constraint 6.5, the frequency reserve requirement constraint 6.6 as well as the non-negativity constraints of variable $x_{v,t}$ and $y_{v,t}$ as Eqn.6.7 and 6.8.

In the objective function, $y_{v,t}$ is the frequency reserve capacity provided by vehicle v. As the reserves need to be provided symmetrically, the capacity $y_{v,t}$ should be able to support both upward and downward regulations. For the SOC limit constraint 6.3, the EV SOC level is calculated through the cumulated charging energy, the activated frequency reserves and the driving energy consumption. In each time interval, the charging plan of each EV should meet the driving energy consumption while the SOC levels of the EV battery are within the specified range in the case of any possible activated frequency reserves for either upward regulations or downward regulations. For the charging energy limit constraint 6.4, the EV charging energy with downward regulations is constrained by the maximum power limit and the EV charging availability. The EV charging availability indicator $s_{v,t}$ shows the status of the EV at time t. It equals to 1 when the EV is parked and available for charging, and it equals to 0 when the EV is not available for charging or regulation operations. The EVs are assumed to be without discharge capability during the frequency reserve regulations in this case. Therefore for the charging energy non-negativity constraint 6.5, the EVs charging energy with upward regulations is constrained to be not less than zero. With constraint 6.4 and 6.5, it is guaranteed that the EVs are able to provide the contracted frequency controlled reserve capacity to the grid. For constraint 6.6, the EV operators are assumed to track the expected frequency controlled reserve requirements of the grid based on the charging availability of the EVs when providing the reserves.

In the formulation above, the EVs are not assumed to discharge their battery during the frequency regulations. In the case when the EVs are assumed to be with the capability of discharge in the regulations, the constraint 6.5 can be revised as Eqn.6.9. During the upward regulations, the EVs can discharge their battery for the response to the frequency deviation in this case. Therefore, the power flow between the EVs and the grid reverses from the normal operations and it is constrained by the connection power limit and the EV charging availability, which is similar to constraint 6.4.

$$x_{v,t} - y_{v,t} \geqslant -p^{+} s_{v,t} \quad \forall t \in T \tag{6.9}$$

For HPs, the detailed mathematical model for the day-ahead energy planning for the electricity spot market and the frequency reserve auction is as follows.

$$\min_{x_{h,t}} \sum_{t \in T} (\alpha_{s,t} x_{h,t} - \alpha_{f,t} y_{h,t} - \alpha_{r,t} E\left[\varphi_t y_{h,t}\right]) \tag{6.10}$$

Subject to

$$T_{in}^{-} \leqslant T_{in,h,t}(\varphi_t) \leqslant T_{in}^{+} \quad \forall \varphi_t \in \varPhi, \forall t \in T \tag{6.11}$$

$$x_{h,t} + y_{h,t} \leqslant \frac{Q_h^{+}}{COP_h} \quad \forall t \in T \tag{6.12}$$

$$x_{h,t} - y_{h,t} \geqslant 0 \quad \forall t \in T \tag{6.13}$$

$$y_{h,t} = \varrho_h \psi_t \quad \forall t \in T \tag{6.14}$$

$$x_{h,t} \geqslant 0 \quad \forall t \in T \tag{6.15}$$

$$y_{h,t} \geqslant 0 \quad \forall t \in T \tag{6.16}$$

where $x_{h,t}$ is the energy purchased for HP h at time t in the day-ahead electricity spot market; $\alpha_{s,t}$ is the electricity spot price at time t in the day-ahead electricity spot market; $y_{h,t}$ is the frequency reserve capacity provided by HP h at time t; $\alpha_{f,t}$ is the price for the frequency-controlled normal operation reserve at time t; $\alpha_{r,t}$ is the regulating power price at time t; φ_t is the activated frequency reserve coefficient at time t; $T_{in,h,t}$ is the temperature of the house interior of HP h; T_{in}^{-} and T_{in}^{+} is the lower and upper temperature limits of the house interior;

Q_h^+ is the heat output limit of HP h; COP_h is the coefficient of performance of HP h; ϱ_h is the frequency reserve provision coefficient of HP h to the reserve requirements of the grid; ψ_t is the expected frequency reserve requirements of the grid at time t; Φ is the set of possible activated reserve coefficients; T is the set of time intervals for the planning.

Similar to the EV case, objective of the HP aggregators is also to maximize their own surplus in the day-ahead electricity spot market and the frequency reserve auctions. The objective function is as Eqn.6.10 minimizing the electrical consumption cost of the HPs minus the avenue of the frequency reserves provided by the HPs and the energy compensation of the activated reserves with regulating power prices subject to the temperature requirement constraint 6.11, the HP heating output limit constraint 6.12, the HP heating output non-negativity constraint 6.13, the frequency reserve requirement constraint 6.14 as well as the non-negativity constraints of variable $x_{h,t}$ and $y_{h,t}$ as Eqn.6.15 and 6.16.

For constraint 6.11, the house interior temperature is limited with the specified range in the case of any possible activated frequency reserves for either upward regulations or downward regulations. For constraint 6.12, the HP heating output with downward regulations is limited by its capacity. The HPs are assumed not to provide energy to the grid, and they reduce their electricity consumption for the upward regulation. Therefore for the heating output non-negativity constraint 6.13, the HP heating output with upward regulations is constrained to be not less than zero. For constraint 6.14, the HP operators are assumed to track the expected frequency controlled reserve requirements of the grid.

Without loss of generality, the thermal dynamics of the houses are as described in Section 4.2.1 and linearized as follows in Eqn.6.17 and 6.18. The indoor temperatures are calculated according to the electricity purchased in the day-ahead spot market $x_{h,t}$ and the activated frequency reserves $\varphi_t y_{h,t}$ based on the environmental profiles including the solar radiation and the environmental temperature.

$$\frac{T_{in,h,t} - T_{in,h,t-1}}{\Delta t} = \frac{(x_{h,t} - \varphi_t y_{h,t})COP_h + \xi_s W Q_{s,t} + C_{is}\left(T_{su,h,t} - T_{in,h,t}\right) + C_{ie}\left(T_{ex,t} - T_{in,h,t}\right)}{C_{in}} \tag{6.17}$$

$$\frac{T_{su,h,t} - T_{su,h,t-1}}{\Delta t} = \frac{\xi_s E Q_{s,t} + C_{is}\left(T_{in,h,t} - T_{su,h,t}\right) + C_{se}\left(T_{ex,t} - T_{su,h,t}\right)}{C_{su}} \tag{6.18}$$

The robust optimization modeling is adopted in the optimization models for the EV and HP day-ahead energy planning mentioned above in order to guarantee the driving and heating requirements of the EVs and HPs with any possible cases of the activated frequency reserves along the day. The set of the activated frequency reserves along the day can be obtained from the historical data with a large enough sample space. However, in such formulation with constraints as Eqn.6.3 and 6.11, it will lead to a case of too many constraints that the model is hard to be solved directly. In order to address this issue, the historical data of the activated frequency reserves along the day is studied and the boundaries of the data is obtained. For example, the system frequency of the Nordic power system from September 2014 to August 2015 is with the activated frequency-controlled normal operation reserve coefficients as shown in Fig.6.3 along the day. The distribution and the boundaries of the activated frequency reserve coefficients can be obtained from the data and are shown in Fig.6.5.

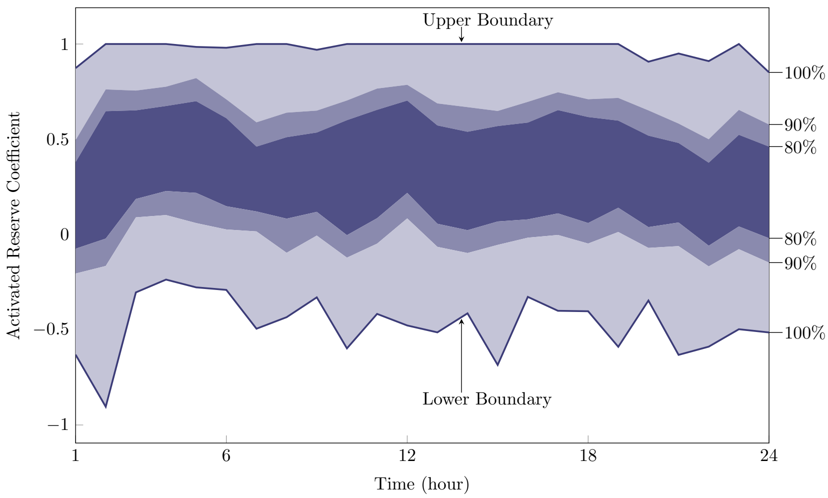


Figure 6.5: Activated Frequency-Controlled Normal Operation Reserves Boundary

The constraint 6.3 and 6.11 in the EV and HP model can be revised using the boundaries of the activated frequency reserve coefficients while keeping the original constraints as Eqn.6.3 and 6.11 satisfied. For EVs, the constraint 6.3 can be revised as Eqn.6.19 and 6.20. For HPs, the constraint 6.11 can be revised as Eqn.6.21 and 6.22.

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - \varphi_\tau^+ y_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall t \in T \tag{6.19}$$

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - \varphi_\tau^- y_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall t \in T \tag{6.20}$$

$$T_{in}^- \leqslant T_{in,h,t}(\varphi_t^+) \leqslant T_{in}^+ \quad \forall t \in T \tag{6.21}$$

$$T_{in}^- \leqslant T_{in,h,t}(\varphi_t^-) \leqslant T_{in}^+ \quad \forall t \in T \tag{6.22}$$

where φ_t^+ is the upper bound of the activated frequency reserve coefficient at time t; φ_t^- is the lower bound of the activated frequency reserve coefficient at time t.

As for all possible $\varphi_t (t \in T)$, the relation $\varphi_t^- \leqslant \varphi_t \leqslant \varphi_t^+$ holds. Therefore, the constraints as Eqn.6.19 and 6.20 guarantee the satisfaction of the constraint as Eqn.6.3 in the EV day-ahead planning. Similarly, the constraints as Eqn.6.21 and 6.22 guarantee the satisfaction of the constraint as Eqn.6.11 in the HP day-ahead planning as well. In such way, the constraint numbers in the optimization models are reduced and consequently the optimization of the EV and HP day-ahead planning can be solved directly in an efficient way.

As discussed in Section 5.3, the electricity spot prices $\alpha_{s,t}$ will be impacted by the flexible demand from EVs and HPs in the day-ahead market. In order to model the behaviors of the EV and HP operators correctly, the aggregative game model with the quadratic programming in Section 5.3 is introduced here. An iteration process is carried out to investigate the equilibrium and obtain the expected electricity spot prices with the EV and HP demand in the day-ahead market. The objective functions of the EV and HP day-ahead planning as Eqn.6.2 and 6.10 are revised as Eqn.6.23 and 6.24 respectively in the optimizations of the ith iteration.

$$\min_{x_{v,t}} \sum_{t \in T}(\alpha_{s,t} x_{v,t} - \alpha_{f,t} y_{v,t} - \alpha_{r,t} E\left[\varphi_t y_{v,t}\right] + \delta(x_{v,t} - x_{v,t}^{(i-1)})^2) \tag{6.23}$$

$$\min_{x_{h,t}} \sum_{t \in T}(\alpha_{s,t} x_{h,t} - \alpha_{f,t} y_{h,t} - \alpha_{r,t} E\left[\varphi_t y_{h,t}\right] + \delta(x_{h,t} - x_{h,t}^{(i-1)})^2) \tag{6.24}$$

where δ is a tracking parameter with a positive constant value; $x_{v,t}^{(i-1)}$ is the optimization solution of the EV day-ahead planning in the $(i-1)$th iteration; $x_{h,t}^{(i-1)}$ is the optimization solution of the HP day-ahead planning in the $(i-1)$th iteration.

The optimizations of the EV and HP day-ahead planning in the iteration process can therefore be expressed with a quadratic optimization model with linear constraints. For EVs, when it is assumed that the EVs can not discharge during regulations, the optimization model is as Eqn.6.25 to 6.32.

$$\min_{x_{v,t}} \sum_{t\in T}(\alpha_{s,t}x_{v,t} - \alpha_{f,t}y_{v,t} - \alpha_{r,t}E\left[\varphi_t y_{v,t}\right] + \delta(x_{v,t} - x_{v,t}^{(i-1)})^2) \tag{6.25}$$

Subject to

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - \varphi_\tau^+ y_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall t \in T \tag{6.26}$$

$$e_v^- \leqslant \sum_{\tau=0}^{t}(x_{v,\tau} - \varphi_\tau^- y_{v,\tau} - d_{v,\tau}) + e_v^0 \leqslant e_v^+ \quad \forall t \in T \tag{6.27}$$

$$x_{v,t} + y_{v,t} \leqslant p^+ s_{v,t} \quad \forall t \in T \tag{6.28}$$

$$x_{v,t} - y_{v,t} \geqslant 0 \quad \forall t \in T \tag{6.29}$$

$$y_{v,t} = s_{v,t}\varrho_v\psi_t \quad \forall t \in T \tag{6.30}$$

$$x_{v,t} \geqslant 0 \quad \forall t \in T \tag{6.31}$$

$$y_{v,t} \geqslant 0 \quad \forall t \in T \tag{6.32}$$

When the EVs are assumed to be with discharge capability during regulations, the constraint 6.29 above should be revised as Eqn.6.33.

$$x_{v,t} - y_{v,t} \geqslant -p^+ s_{v,t} \quad \forall t \in T \tag{6.33}$$

For HPs, the optimization model is as Eqn.6.34 to 6.41

$$\min_{x_{h,t}} \sum_{t\in T}(\alpha_{s,t}x_{h,t} - \alpha_{f,t}y_{h,t} - \alpha_{r,t}E\left[\varphi_t y_{h,t}\right] + \delta(x_{h,t} - x_{h,t}^{(i-1)})^2) \tag{6.34}$$

Subject to

$$T_{in}^- \leqslant T_{in,h,t}(\varphi_t^+) \leqslant T_{in}^+ \quad \forall t \in T \tag{6.35}$$

$$T_{in}^- \leqslant T_{in,h,t}(\varphi_t^-) \leqslant T_{in}^+ \quad \forall t \in T \tag{6.36}$$

$$x_{h,t} + y_{h,t} \leqslant \frac{Q_h^+}{COP_h} \quad \forall t \in T \tag{6.37}$$

$$x_{h,t} - y_{h,t} \geqslant 0 \quad \forall t \in T \tag{6.38}$$

$$y_{h,t} = \varrho_h \psi_t \quad \forall t \in T \tag{6.39}$$

$$x_{h,t} \geqslant 0 \quad \forall t \in T \tag{6.40}$$

$$y_{h,t} \geqslant 0 \quad \forall t \in T \tag{6.41}$$

Both of the optimization problems are with a standard convex quadratic optimization formulation and can be solved efficiently given that the constraints can be satisfied. In the ith iteration, the electricity spot prices $\alpha_{s,t}$ is updated with the optimization solutions of the EV and HP day-ahead planning in the $(i-1)$th iteration as follows.

$$\alpha_{s,t} = \alpha_{s,t}^0 + \beta \left(\sum_{v \in V} x_{v,t}^{(i-1)} + \sum_{h \in H} x_{h,t}^{(i-1)} \right) \tag{6.42}$$

where $\alpha_{s,t}^0$ is the predicted baseline spot price according to the conventional demand at time t; β is the coefficient of spot price on the electrical demand; V is the set of EVs in the grid; H is the set of HPs in the grid.

In the formulation above, a quadratic term is introduced in the objective functions of the EV and HP day-ahead planning. With the quadratic term in the objective function, the solutions of optimizations in the iteration process converge to the optimal solutions given the collective behaviors of all the EVs and HPs in the grid instead of oscillating as in the case with the linear modeling. No extra cost is added to the planning as the quadratic term is eliminated when the iterations converge. Therefore, the solution through the iteration process converge to the optimal solution with the electricity spot prices when the flexible demand of EVs and HPs in the grid is the same as the solution itself.

6.4 Numerical Case Studies

In order to investigate the feasibility and capacity of EVs and HPs to provide frequency-controlled reserves to the power system, a case study of Denmark is carried out. The details and results of the case study are presented in this section.

The iteration process with the quadratic programming described in Section 6.3 is adopted in the case study to obtain the equilibrium in the electricity day-ahead market. For EVs, a 100% penetration level in Denmark is assumed in the case study. All the private passenger cars are assumed to be EVs. Currently, about 69% of the residential heating demand in Denmark is supplied by district heating or sustainable resources. All the rest of the residential heating is assumed to be provided by HPs in the case study. The EV number in the case study is 2.1×10^6, the HP number in the case study is 8.0×10^5.

6.4.1 Scenario Descriptions

For the purpose of achieving a more comprehensive understanding of the capability of EVs and HPs to provide frequency-controlled reserves, three different scenarios are performed in the case study. Scenario 1 is the base case with mild environmental profiles and an ordinary EV energy consumption rate, while the EVs have no capability of discharge in the frequency-controlled reserve operations; Scenario 2 has the same environmental profiles and EV energy consumption rate as Scenario 1, while the EVs have the capability of discharge in the frequency-controlled reserve operations; Scenario 3 is the case with more intense environmental profiles and a higher EV energy consumption rate compared to the base case in Scenario 1.

The driving patterns of the EVs in the study are obtained from the Denmark National Travel Surveys as described in Section 3. The key parameters of the EVs in the study are listed in Tab.6.2. In the Nordic context, the EVs tend to consume more under a colder temperature. In the mild case for Scenario 1 and 2, the average EV energy consumption rate is set to be 150Wh/km. In the intense case for Scenario 3, the average EV energy consumption rate is set to be 200Wh/km.

The thermal dynamic of the houses is modeled according to Eqn.6.17 and 6.18. The environmental weather parameters are as listed in Tab.6.3. The environmental parameters of the mild and intense scenarios including the ambient temperature and solar radiation profiles adopt the data in Copenhagen in October and January, respectively. The interior temperature preference is set in the range 20-24°C. The COP of the HPs is set to be 3.1375. The sizes of the houses are uniformly random from 40 to 250m^2. The capacity of the heat pumps is set according to the size of the houses. For the houses with an area less than 90m^2, the capacity of the heat pump is set to be 5kW; for the houses with an

Table 6.2: EV Parameters in Case Study

Parameter	Value
EV battery capacity	60kWh
Charging power limit	10kW
Energy consumption per km	150Wh/km (Scenario 1, 2) 200Wh/km (Scenario 3)
Lower SOC level limit	20%
Upper SOC level limit	85%

area between 90 to 150m^2, the capacity of the heat pump is set to be 10kW; for the houses with an area over 150m^2, the capacity of the heat pump is set to be 15kW.

Table 6.3: Environment Profiles of the Mild and Intense Scenarios in the Case Study

Hour	Ambient Temperature (°C)		Solar Radiation (W/m^2)	
	Mild Scenario	Intense Scenario	Mild Scenario	Intense Scenario
1	2.7	-2.0	0	0
2	2.0	-2.3	0	0
3	1.1	-2.6	0	0
4	-1.2	-2.6	0	0
5	-0.9	-2.6	0	0
6	1.4	-2.6	0	0
7	1.3	-2.7	15.9	0
8	1.9	-2.9	77.6	32.2
9	3.1	-2.7	149.7	123.3
10	5.4	-2.0	213.5	151.6
11	7.1	-1.5	246.8	149.8
12	7.5	-0.9	243.8	196.3
13	7.7	-0.3	185.7	198.2
14	7.5	0.1	116.4	173.0
15	7.1	-0.2	56.3	98.1
16	6.0	-0.5	6.6	16.1
17	4.1	-1.1	0	0
18	3.7	-1.2	0	0
19	3.4	-1.4	0	0
20	3.5	-1.3	0	0
21	3.2	-1.3	0	0
22	2.5	-1.4	0	0
23	1.7	-1.3	0	0
24	0.9	-1.1	0	0

The predicted baseline spot price with the conventional demand α_t^0 is assumed as shown in Appendix B. The historical data in the day-ahead market of Denmark is studied. The coefficient of spot price on the electrical demand β is set to be with the value of 0.0036EUR/MW in the case study accordingly. In the Nordic regulating power market, a two-price system is held for the balance providers at present. For the power deviation which helps to address the total imbalance of the grid, the regulating power price is the same as the spot price. Therefore, the regulating power prices are set to be the same as the spot prices in the case study. The price for the frequency-controlled normal operation reserve $\alpha_{f,t}$ is assumed as shown in Appendix C.

6.4.2 Case Study Results

6.4.2.1 Results of Scenario 1

Scenario 1 serves as a base case in the study. It is with the mild environmental profiles listed in Tab.6.3. The average EV energy consumption rate is assumed to be 150Wh/km and the EVs are assumed to be without the capability of discharge in the frequency-controlled reserve operations.

Fig.6.6 shows the day-ahead energy plans of the EVs and HPs as well as the frequency-controlled normal operation reserve capacity the EVs and HPs can provide to the grid in Denmark in Scenario 1.

As shown in the figure, the HPs consume more electricity during the low-spot-price period at night and less in the day when there are higher temperatures and more solar radiation. Due to the fact that the reserves are purchased as a symmetric product, the energy plans of EVs need to be able to perform both upward regulations and downward regulations. As the EVs are assumed not to discharge during the regulations in Scenario 1, the demand of EVs spread out along the day in the day-ahead energy plan in order to provide more frequency reserves to the grid. Consequently, the EVs can reduce their demand for the upward regulations when activated. Both of the EVs and HPs can provide considerable capacity of frequency-controlled normal operation reserves to the power system along the day. On average, the reserve capacity from the EVs and HPs are 731MW and 457MW respectively in Denmark in Scenario 1 of the case study.

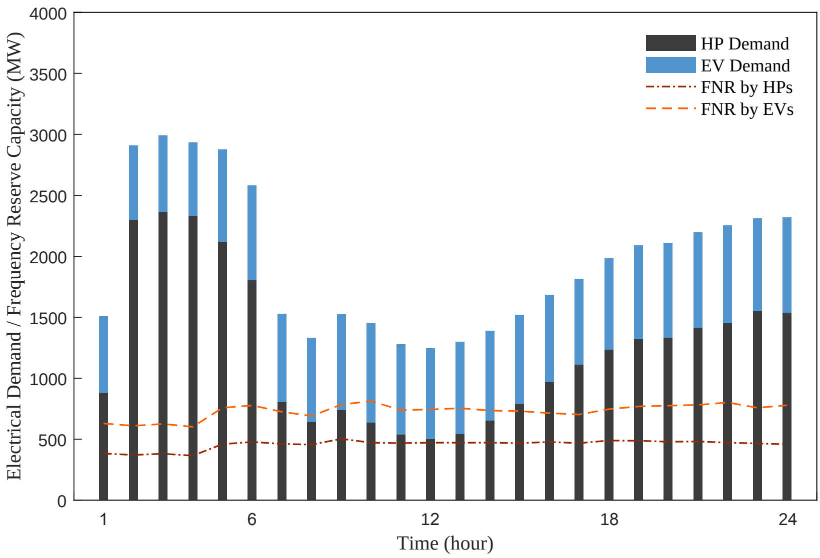


Figure 6.6: Day-ahead Energy Plans of EVs and HPs Providing FNR in Scenario 1

6.4.2.2 Results of Scenario 2

Scenario 2 is carried out in order to investigate the impact of the EVs' capability of discharge in the frequency-controlled reserve operations. Similar to Scenario 1, it is with the mild environmental profiles listed in Tab.6.3 and the average energy consumption rate of EVs is assumed to be 150Wh/km. However, the EVs are assumed to be able to discharge the batteries to provide upward regulations in the frequency-controlled reserve operations in this case.

Fig.6.7 shows the day-ahead energy plans of the EVs and HPs as well as the frequency-controlled normal operation reserve capacity the EVs and HPs can provide to the grid in Denmark in Scenario 2.

As shown in the figure, the demand of EVs converges at night when the electricity spot prices are the low instead of spreading through out the day as the case in Scenario 1. The EVs are assumed to be able to discharge during the regulations in this Scenario. Although the reserves are purchased as a symmetric product, the EVs are able to perform upward regulations by discharging the batteries when activated. As a result, different from Scenario 1, the demand of EVs mainly locates at night in Scenario 2 in order to minimizing the charging cost. Both of the EVs and HPs can provide considerable capacity of frequency-

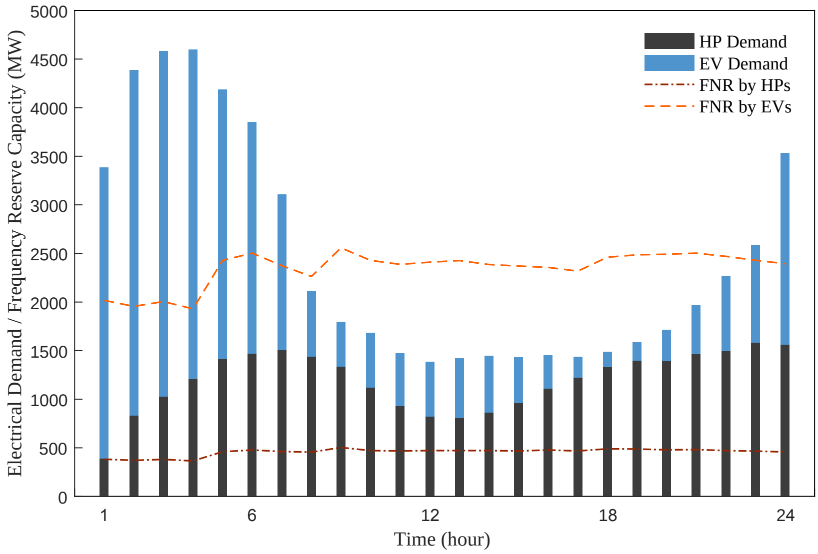


Figure 6.7: Day-ahead Energy Plans of EVs and HPs Providing FNR in Scenario 2

controlled normal operation reserves to the power system along the day. Due to the capability of discharge in Scenario 2, the capacity of the EV battery is further utilized and consequently the reserve capacity from EVs increases by twice compared to Scenario 1. On average, the reserve capacity from the EVs and HPs are 2348MW and 457MW respectively in Denmark in Scenario 2 of the case study.

6.4.2.3 Results of Scenario 3

Scenario 3 is carried out in order to investigate the impact of the environmental weather conditions on the capability of EVs and HPs to provide the frequency reserves. It is with the intense environmental profiles listed in Tab.6.3 which describes a colder weather environment compared to Scenario 1. The average EV energy consumption rate is assumed to be 200Wh/km. The EVs are assumed to be without the capability of discharge in the frequency-controlled reserve operations.

Fig.6.8 shows the day-ahead energy plans of the EVs and HPs as well as the frequency-controlled normal operation reserve capacity the EVs and HPs can provide to the grid in Denmark in Scenario 3.

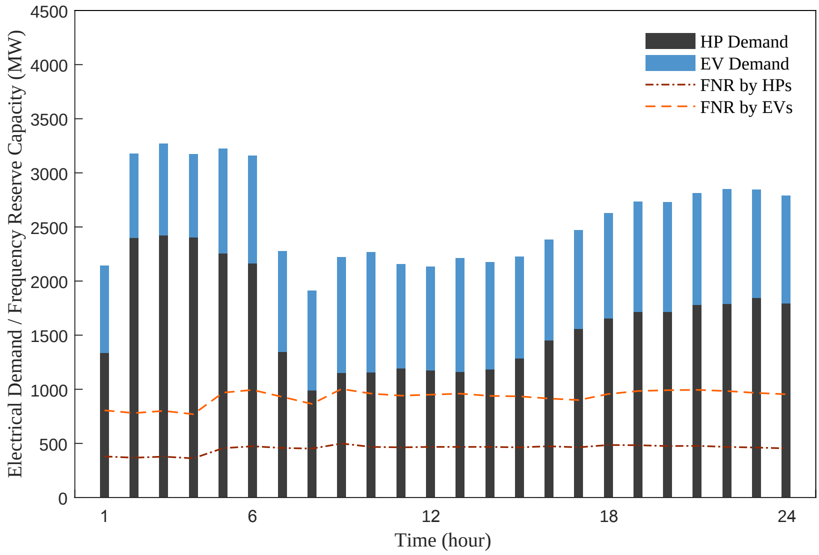


Figure 6.8: Day-ahead Energy Plans of EVs and HPs Providing FNR in Scenario 3

Similar to Scenario 1, the HPs consume more electricity during the low-spot-price period at night and the demand of EVs spread out along the day in the day-ahead energy plan in order to provide more frequency reserves to the grid. Due to a more intense environmental condition and a higher energy consumption rate of EVs, the demand of both the HPs and EVs is higher than Scenario 1. Both of the EVs and HPs can provide considerable capacity of frequency-controlled normal operation reserves to the power system along the day. The reserve capacity from HPs in Scenario 3 is more or less the same as Scenario 1. It is because of the fact that the HP output is mainly constrained by the indoor temperature limits in this case. However, the reserve capacity from EVs in Scenario 3 is about 25% higher than Scenario 1. As the EVs are assumed to be without capability of discharge in this case, they can only reduce their demand in order to perform upward regulations. Therefore, the reserve capacity from EVs increases in Scenario 3 with a higher driving energy consumption. On average, the reserve capacity from the EVs and HPs are 927MW and 453MW respectively in Denmark in Scenario 3 of the case study.

Chapter 7

Conclusion and Future Work

The Ph.D. study in this thesis investigates the demand of large scale deployment of EVs and HPs in the Nordic countries including Denmark, Finland, Norway and Sweden. The demand of the EVs and HPs is modeled under different contexts with the detailed driving and heating requirements considered. The possibility of the EV and HP demand to provided frequency reserves to the power system is also investigated in the study.

7.1 Conclusions

- The market share of EVs and HPs in the Nordic countries is still at a fairly low level at present. However, both of the EV and HP markets have been experiencing a rapid increase in the Nordic region in recent years. The private passenger transportation sector and the space heating sector play important roles in the energy systems of the Nordic countries. EVs and HPs have extensive prospects in these two sectors of the Nordic region.
- The daily driving patterns of the vehicles in the Nordic region are investigated based on the National Travel Surveys of the Nordic countries. The daily driving distance is moderate in the area. Most of the daily driving behaviors are in the low-distance range. Such low daily driving distance is beneficial to the EV deployment. However, it is worth noting that the

average driving distance in Finland on weekends is higher than the other three countries. The charging availability of vehicles in the Nordic countries is fairly high along the day. On the other hand, when the case is strict to home charging, the availability of EVs is significantly lower in the day time on weekdays. However, the availability is still at a high level at night even though only the home connection is considered available to the EVs in this case.

- The electrical demand of EVs and HPs under non-market environments is modeled with the detailed driving and heating requirements in the Nordic countries. The EV demand is modeled with the uncontrolled charging schemes and the timed charging scheme. With the uncontrolled charging scheme, whether it is home charging or not, the peak EV charging demand coincides with the peak hours of the conventional demand of the power system. With the timed charging scheme, the EV charging demand is delayed to avoid the conventional peak demand to some extend. However, most of the charging congregates in a short period when the timed charging is set started. The HP demand is modeled with a least-energy-consumption control scheme. With the control scheme, the HP demand is consistent with the environmental weather profiles. The demand is high in the evening and at night when the temperatures and the solar radiation are low, and the demand is low in the middle of the day when the temperatures and the solar radiation are high. The increasing HP demand in the evening coincides with the peak hours of the conventional demand of the power system which may stress the grid.
- A chance constrained programming model is proposed to formulate the EV demand in the day-ahead electricity market considering the stochastic characteristics of the driving patterns of the vehicles. The chance constrained programming model is analyzed and formulated through a mixed-integer programming model in order to address the difficulties in solving the original standard formulation of the chance constrained programming model. The MIP model can handle the stochastic characteristics of the EV driving patterns and guarantee that the driving requirements of the EVs are met by the day-ahead energy planning with the predefined confidence level.
- A robust optimization model is proposed to formulate the HP demand in the day-ahead electricity market considering the uncertainty of the weather forecast used in the HP energy planning. The heating requirements for the HPs are guaranteed by the day-ahead energy plans through the robust optimization model to handle the uncertainty in the weather forecast .
- An aggregative game model is proposed to model the demand of large scale deployment of EVs and HPs in the day-ahead electricity market. The

impacts of the EV and HP demand on the electricity spot price in the day-ahead market are considered in the proposed game model when the EV and HP day-ahead energy planning is carried out. The equilibrium of the game model is solved through an iteration process with a quadratic optimization model while the original objectives of the EV and HP operators in the day-ahead market are reached and the constraints of the EVs and HPs are respected. With a high penetration level, the demand of EVs and HPs shows a "valley-fill" pattern to the grid when it is introduced into the day-ahead electricity market.

- A combined modeling of the EV and HP energy planning is proposed for both the energy plans in the day-ahead electricity market and the frequency reserve provision decisions in the ancillary service market considering the detailed driving and heating requirements. The impacts of the EV and HP demand on the electricity spot price in the day-ahead market are considered through the aggregative game model. It is shown that both EVs and HPs can provide considerable frequency reserves to the power system along the day in the Nordic region. V2G technologies which enable the EVs to discharge the batteries in the reserve operations can further utilize the capacity of the EVs and consequently increase the ability of EVs to provide frequency reserves to the power system. Further, the intense weather of the Nordic region in winter does not decrease the ability of EVs and HPs to provide frequency reserves to the power system.

7.2 Future Work

The work in the Ph.D. study has carried out some attempts to investigate the modeling of the EV and HP demand, especially under a Nordic context. The flexibility of the EVs and HPs is also in the scope of the research. However, in order to obtain a full understanding on the impacts of the large scale deployment of EVs and HPs on the power system, a lot of work remains to be done. Following are some suggestions for the future work.

- The modeling of the EV and HP demand in the day-ahead electricity market and the possibility of EVs and HPs to take part in the frequency reserve market is studied in the Ph.D. study. To further explore the utilization of the flexibility of EV and HP demand in the future power system, the possible market mechanism for the coordinated scheduling of renewable energy (e.g. wind power) and the flexible demand from EVs and HPs can be investigated.

- The impacts of the flexible demand from EVs and HPs on the power system are not only related to the time distribution but also the location distribution of the demand, especially for EVs. The combined spatial and temporal modeling of the EV and HP demand can be further investigated and will benefit the relative researches of the power system.
- The impacts of the demand of the large scale deployment of EVs and HPs on the power system stability also need to be investigated in order to accommodate the flexible demand while keeping the power system operated securely. Either the frequency stability, the angle stability or the voltage stability of the system shall be in the scope of the researches.

Appendix A

Cumulative Daily Driving Distance Distribution in the Nordic Region

A.1 Cumulative Daily Driving Distance Distribution in the Nordic Region on Weekdays

The cumulative daily driving distance distribution in the Nordic region on weekdays is as shown in Tab.A.1.

A.2 Cumulative Daily Driving Distance Distribution in the Nordic Region on Weekends

The cumulative daily driving distance distribution in the Nordic region on weekends is as shown in Tab.A.2.

Table A.1: Cumulative Daily Driving Distance Distribution in the Nordic Region on Weekdays

Distance (km)	Denmark (%)	Finland (%)	Norway (%)	Sweden (%)
0	19.7	19.6	24.8	26.6
10	32.7	33.0	41.6	42.8
20	45.8	46.4	55.3	55.8
30	56.2	57.6	64.8	66.2
40	64.3	65.1	72.6	73.8
50	71.2	71.4	78.3	79.9
60	76.6	76.5	82.0	84.8
70	80.9	80.8	85.0	88.2
80	84.3	83.8	87.3	90.5
90	87.0	86.2	89.6	92.3
100	89.2	88.0	91.1	93.4
150	95.1	93.7	95.5	96.9
200	97.5	96.2	97.5	98.2
250	98.5	97.7	98.4	98.8
300	99.1	98.4	98.8	99.2
350	99.4	99.1	99.3	99.4
400	99.6	99.4	99.5	99.5
450	99.8	99.7	99.7	99.7
500	99.8	99.8	99.7	99.7
600	99.9	99.8	99.9	99.9
700	100	99.9	99.9	99.9
800	100	99.9	100	100

Table A.2: Cumulative Daily Driving Distance Distribution in the Nordic Region on Weekends

Distance (km)	Denmark (%)	Finland (%)	Norway (%)	Sweden (%)
0	36.0	26.7	39.8	32.1
10	50.9	38.9	54.4	51.3
20	62.6	46.4	55.3	55.8
30	70.2	50.5	65.3	63.3
40	75.9	60.2	72.7	72.0
50	80.6	65.5	77.8	78.4
60	84.0	71.1	81.6	82.6
70	86.6	74.9	84.3	86.2
80	88.9	78.3	86.8	88.4
90	90.5	80.8	88.3	89.9
100	91.9	83.1	90.1	91.9
150	95.7	84.7	91.1	92.8
200	97.7	91.2	94.0	96.2
250	98.6	94.2	96.1	97.6
300	99.2	96.0	97.5	98.3
350	99.5	97.3	98.7	98.9
400	99.7	98.0	99.4	99.4
450	99.8	98.9	99.8	99.6
500	99.9	99.3	99.8	99.8
600	100	99.6	99.9	100
700	100	99.9	99.9	100
800	100	100	100	100

Appendix B

Spot Price of Electricity in the Case Studies

The electricity spot price in the case studies is as shown in Tab.B.1 and Fig.B.1.

Table B.1: Spot Price of Electricity in the Case Studies

Hour	Price (EUR/MWh)	Hour	Price (EUR/MWh)
1	25.06	13	33.06
2	22.43	14	33.08
3	22.16	15	33.35
4	20.50	16	33.62
5	24.43	17	33.92
6	25.77	18	33.98
7	28.53	19	33.77
8	31.95	20	33.30
9	32.87	21	32.55
10	32.80	22	31.54
11	33.14	23	30.57
12	33.21	24	27.12

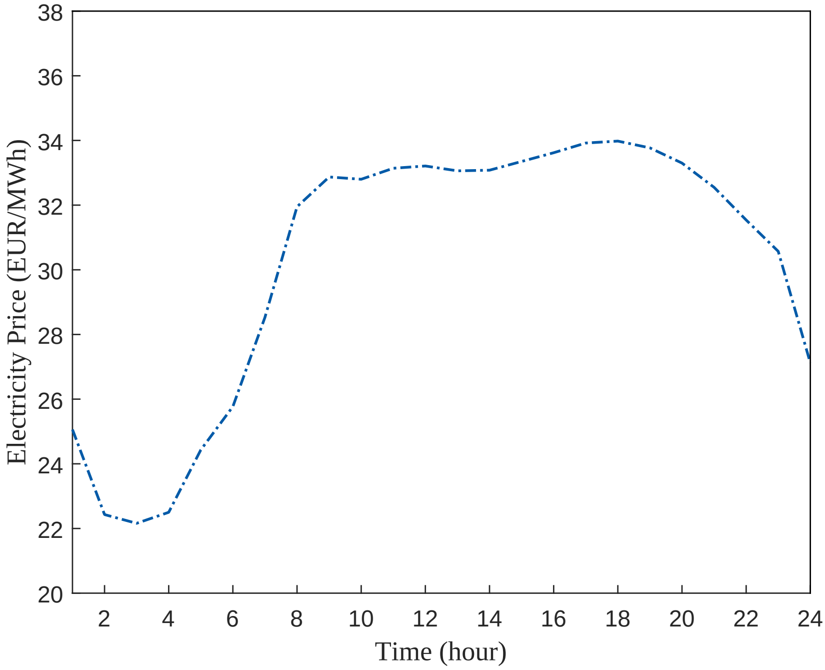


Figure B.1: Spot Price of Electricity in the Case Studies

Appendix C

Frequency Reserve Price for the Case Studies

The price for the frequency-controlled normal operation reserve in the case studies is as shown in Tab.C.1.

Table C.1: Frequency Reserve Price in the Case Studies

Hour	Price (EUR/MWh)	Hour	Price (EUR/MWh)
1	55.42	13	36.75
2	55.39	14	36.65
3	56.39	15	36.44
4	57.64	16	37.81
5	57.64	17	30.76
6	57.43	18	30.74
7	54.91	19	30.65
8	52.60	20	30.61
9	35.94	21	35.97
10	37.61	22	35.17
11	37.56	23	37.04
12	37.62	24	39.38

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