EV Charging Analysis with High EV Penetration in the Nordic Region

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Executive Summary

This report covers the driving pattern analysis and the electric vehicle (EV) charging ananlysis of Denmark, Sweden, Norway and Finland. The contents in the report are driving pattern analysis of the passenger cars and electrical charging load profiles of EVs based on the analyzed driving patterns in the four mentioned Nordic countries.

The driving pattern analysis is based on the National Travel Survey of Denmark, Sweden, Norway and Finland. For Denmark, the driving pattern is obtained from the detailed EV grid integration analysis in Denmark by Technical University of Denmark (DTU) [1]. The analysis offers a detailed study of the driving pattern of passenger cars which is based on the Danish Transport Survey data (TU data). For the Swedish, Norwegian and Finnish cases, the driving status is indicated by the start time, the ending time and the driving distance of each trip with the respondent as a passenger car driver from the datasets of the National Travel Survey of the three countries. The resolution of the data is in minute. In such a way the EV charging availability of passenger cars throughout the day is generated. According to the analysis, most of the daily trips in the Nordic region are with a relatively short distance. For around 70% to 78% of the passenger cars have a daily driving distance within 45km. The patterns of the EV charging availability in the four countries are similar to each other. If only the driving time periods of the vehicle are considered as the unavailable periods, the availability is at a high level for over 90%. On weekdays, there are two valleys in the availability curves in the morning and the evening when people are supposed to go to work and go home. On weekends, the availability drops gradually in the morning and rises again from the afternoon to the night. However, if the vehicles are supposed to be only charged at home, the EV charging availability of all the four countries shows to be much lower. On weekdays, the availability begins to decrease in the morning when people leave home for work and stays on a low level until people are supposed to go home in the evening. On weekends, the availability decreases in the morning and climbs up gradually from the afternoon to the night.

Based on the driving pattern analysis mentioned above, the EV charging analyses of Denmark, Sweden, Norway and Finland are conducted. In the EV charging analysis, each vehicle is charged according to its own driving pattern with different types of charging patterns, including dumb charging, timed charging and spot price based charging. Three different typical charging rates are applied in the charging analysis including 2.3kW for 1 phase 10A charging, 3.68kW for 1 phase 16A charging and 11.04kW for 3 phase 16A charging. The electrical charging curves of all the studied vehicles are averaged to obtain the mean charging load of one vehicle with different charging patterns and charging rates respectively. The mean charging load curves are scaled up by the passenger car numbers of the four mentioned Nordic countries to get the total EV charging load curves respectively.

The patterns of the charging load curves are different accroding to the charging patterns and the charging rates. For dumb charging, the peak charging load overlaps the peak hours of the original electric load in the evening on weekdays, which would worsen the case for the electric power system. Timed charging has a high charging peak load when most of the charging starts at the same time period. The spike of the EV charging load with timed charging is so steep that it results in a high peak in the total electric load. The spot price based charging, to some extent, moves the majority of the charging demand to the low demand period of the electric power grid at night. However, most of the charging congregates in the hour of lowest electric spot price and generates a high peak load as a result. With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves are sharper, which is the same for all charging patterns.

The study in this report offers an overview of the charging load with large scale deployment of EVs in the Nordic region. The amount of the EV charging load tends to be considerable when the EV penetration level is high in all the four mentioned Nordic countries. However, there are some factors which are not included in this report, such as the stochastic characteristic of the driving patterns of passenger cars, the interplay of the massive EV charging load and the electric power grid, etc. Future work shall be done in these related areas in order to achieve a deeper look at the impact of the EV charging load to the electric power system.

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DER	Distributed Energy Resources
EVs	Electric Vehicles
GHG	Greenhouse Gas
RES	Renewable Energy Source

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1 Introduction

The Nordic region, including Denmark, Sweden, Norway and Finland, shows ambitions in achieving a carbon neutral electric power system in a time perspective up to 2050. Electric vehicles (EVs) considered as a kind of distributed energy resources (DER), hold a potential to cope with the intermittency from the further utilization of renewable energy sources (RES) in the Nordic power grid. Furthermore, the worldwide concern about the greenhouse gas (GHG) emission has motivated the development of EVs in the past few decades. With such impetus the study on the electrification in the transportation sectors with large-scale deployment of EVs shows strong necessity in the four mentioned Nordic countries.

Previous study has been done on the general electric demand of the large-scale deployment of EVs in the Nordic region [2]. However, the electrical charging profiles of EVs have strong relationships with a number of factors including the driving patterns, the charging strategies and the rating of charging power. This report is to investigate the EV charging load based on the driving patterns with different charging patterns and different rates of charging power in the Nordic region.

With a large-scale deployment of EVs, the driving requirement of the current vehicle users should be met. Therefore, it is meaningful to study the driving pattern of the present internal combustion engine vehicles. The study in this report focuses on the private passenger cars and analyzes the datasets from the National Travel Surveys of Denmark, Sweden, Norway and Finland. The driving requirements with detail driving patterns of the four Nordic countries are obtained respectively.

With the driving patterns based on the National Travel Surveys, the EV charging analyses are carried out accordingly. The EV charging analyses of the four Nordic countries in this report, as cited previously, have considered the impact of the EV charging patterns and the EV charging power rating. The studied charging patterns include dumb charging, timed charging and spot price based charging. Further, the influence of the charging availability whether the EVs can only be charged at home or can be charged whenever the vehicles are parked is also analyzed in the study of this report.

This report is arranged as follows.

Chapter 2 covers the daily driving pattern study based on the National Travel Surveys of Denmark, Sweden, Norway and Finland. The driving patterns of the four mentioned Nordic countries are analyzed respectively. Chapter 3 covers the EV charging analysis of the four Nordic countries based on the driving pattern analysis presented in chapter 2. Finally, in chapter 4, conclusions are drawn on both the driving pattern analysis and EV charging analysis of the Nordic region.

2 Driving Pattern Analysis in the Nordic Region

In order to analyze the charging schedule of EVs in the Nordic region, it is necessary to study the driving pattern of EVs in the area. It is difficult to obtain the driving pattern of EVs directly in that there are few EVs on the road currently. However, with a high penetration level of EVs and sufficient support of charging, the driving pattern of EVs will show more or less the same as the traditional passenger cars when or if all the driving requirements are fulfilled. Therefore, it is reasonable to use the driving pattern of normal passenger cars in the Nordic area to estimate the driving pattern of EVs. In this chapter, the method of the driving pattern analysis of Denmark, Sweden, Norway and Finland are first introduced. After that, the analyzed driving profiles of the four Nordic countries are presented respectively. Finally, a summary over the driving patterns of the four mentioned Nordic countries is given.

2.1 Method of Driving Pattern Analysis in the Nordic Region

The driving pattern in the analysis includes the start and ending time of each trip, which are used to determine the available time slots for EV charging and discharging; the driving destination of each trip, which is used to determine the availability of EVs for charging and discharging during the parking time slot; the driving distance of each trip, which is used to calculate the charging energy requirement of the EVs. The procedure of the EV availability analysis is illustrated in the flow chart shown in Figure 2-1.

For Denmark, the driving pattern is obtained from the detailed EV grid integration analysis in Denmark by Technical University of Denmark (DTU) [1]. The analysis offers detailed study on the driving pattern of passenger cars which is based on the Danish Transport Survey data (TU data). The driving pattern consists of time periods when cars are being driven, time periods when cars are parked, and driving distance of each trip for cars of different user groups and different days within one week.

For the Swedish study case the driving pattern analysis is based on the data from Swedish National Travel Survey 2012. The observations in the dataset are following the respondents instead of the passenger cars. In order to estimate the driving pattern of the passenger cars, the observations of the respondents who has one car or more and a driving license are recorded. The driving status, indicated by the start time, the ending time and the driving distance of each trip with the respondent as a passenger car driver is obtained by minutes. In this way the driving status throughout the day is generated. Regarding the average driving distance of passenger cars, there is a slight difference between the result from the process mentioned above and the figure from Statistic Sweden. In order to be consistent with the figure from Statistic Sweden, a coeffient is applied on the driving distance in the driving pattern analysis.

The Norwegian study case is based on Norwegian National Travel Survey 2009 and the Finnish study case is based on Finnish National Travel Survey 2010-2011. Similar processes as that of the Swedish study case mentioned above are carried out for both the Norwegian driving pattern analysis and the Finnish driving pattern analysis, respectively.

For all the study cases of the four mentioned Nordic countries, the analysis is limited to registered private passenger cars. Two different kinds of EV charging availability are studied in this chapter. EV availability (All-Day) refers to the charging availability whenever the car is parked throughout the day. On the other hand, EV availability (At-Home) refers to the charging availability only when the car is parked at home.

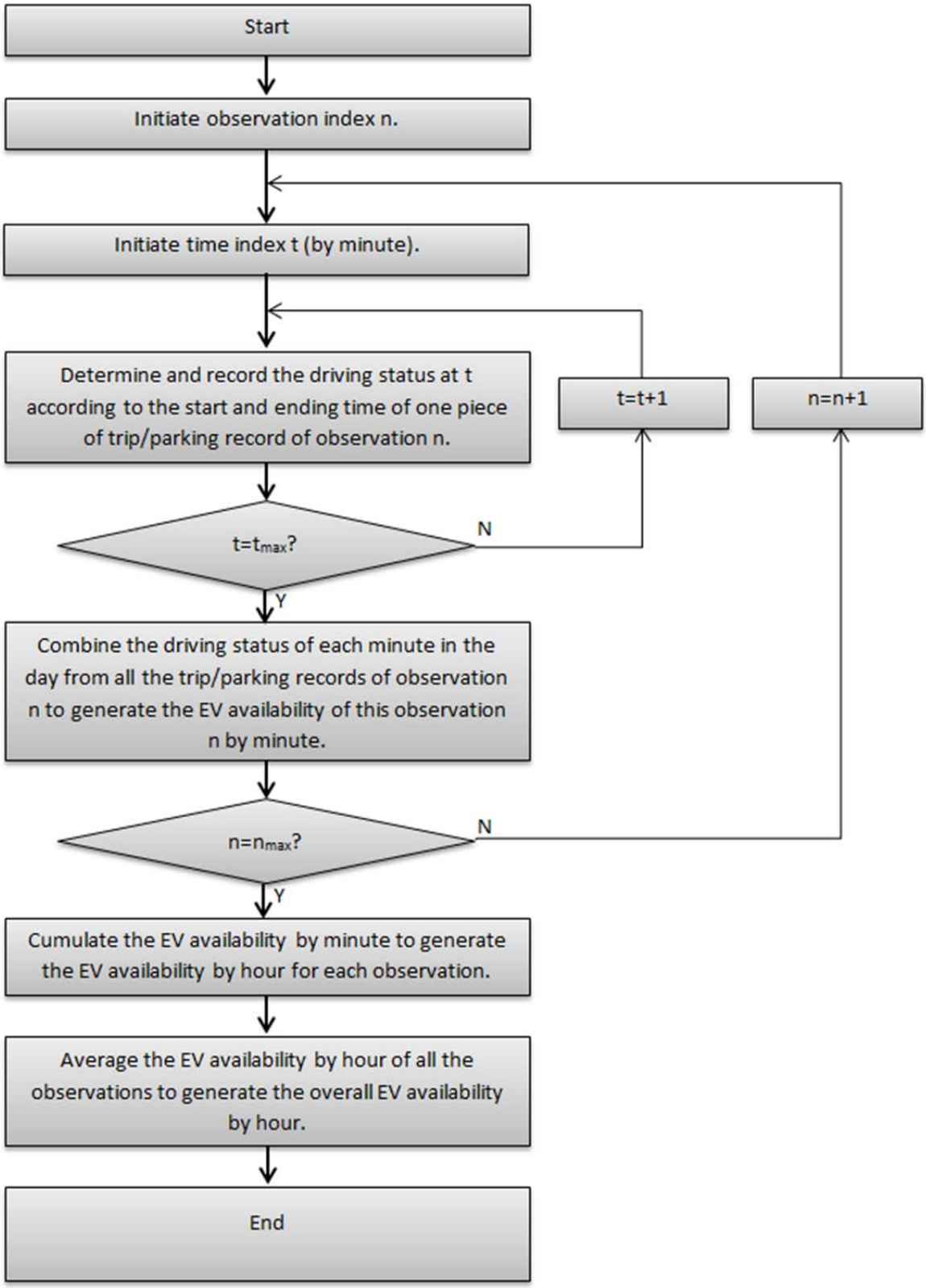

Figure 2-1 Procedure of the EV Availability Analysis

2.2 Driving Pattern Analysis in Denmark

A detailed analysis on the driving pattern of Denmark passenger cars has been carried out by DTU [1]. The analysis is based on the Danish Transport Survey data (TU data) which are the interview data collected daily for over 15 years and comprise more than 100000 survey results. The average driving distance data are listed in Table 2-1. The overall average daily driving distance is about 40km. For weekdays, the average driving distance is 44km. The average driving distances of Saturday and Sunday are 34km and 30km, respectively. The average dirving distance in Denmark is in a reasonable distance which can be supported by the current EV technology. According to the data from Danmark Statistik, the personal car numbers in Denmark is 2.09 millions [1].

Table 2-1 Average Driving Distance Data in Denmark

Day Type	Average Driving Distance [km]
All days	40.2
Weekdays	43.6
Saturday	34.2
Sunday	30.0

The individual and cumulative driving distance distributions are illustrated in Table 2-2, Figure 2-2 and Figure 2-3. It is shown that about 70.2% of the passenger cars have a daily driving distance of 45km or less.

Table 2-2 Driving Distance Distribution in Denmark

Driving Distance [km]	Individual [%]	Cumulative [%]
0	29.05	29.05
10	14.26	43.31
20	11.36	54.67
30	8.75	63.42
40	6.78	70.19
50	5.75	75.95
60	4.27	80.22
70	3.45	83.67
80	2.85	86.52
90	2.15	88.67
100	4.40	93.06
150	3.44	96.50
200	1.57	98.07
250	0.78	98.85
300	0.41	99.26
350	0.29	99.55
400	0.19	99.74
450	0.08	99.82
500	0.08	99.90
600	0.05	99.96
700	0.02	99.98
800	0.01	99.99
900	0.01	100.00
1000	0.00	100.00

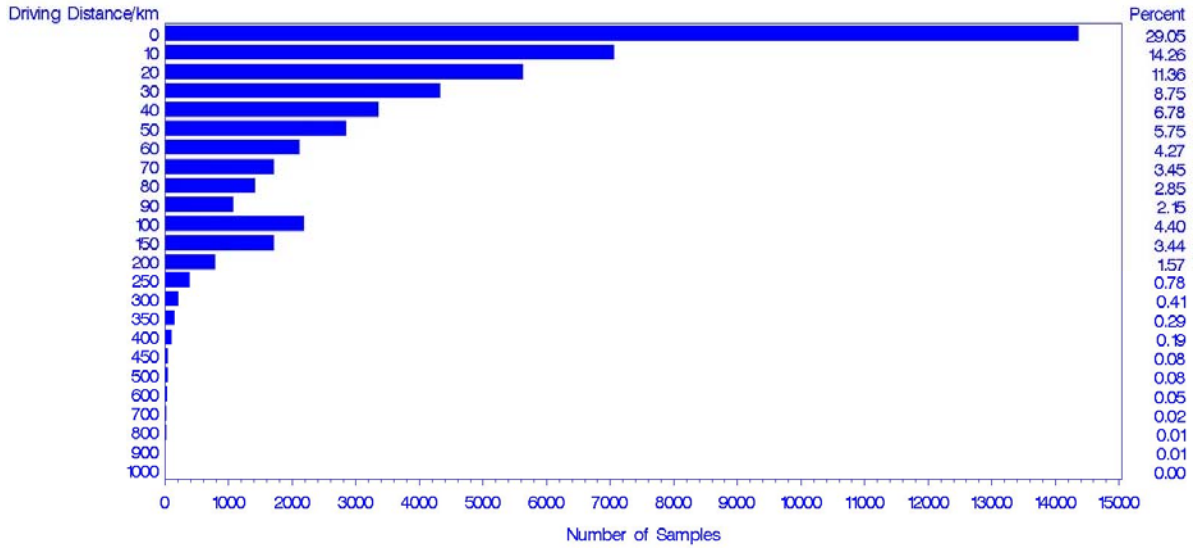

Figure 2-2 Individual Driving Distance Distribution in Denmark

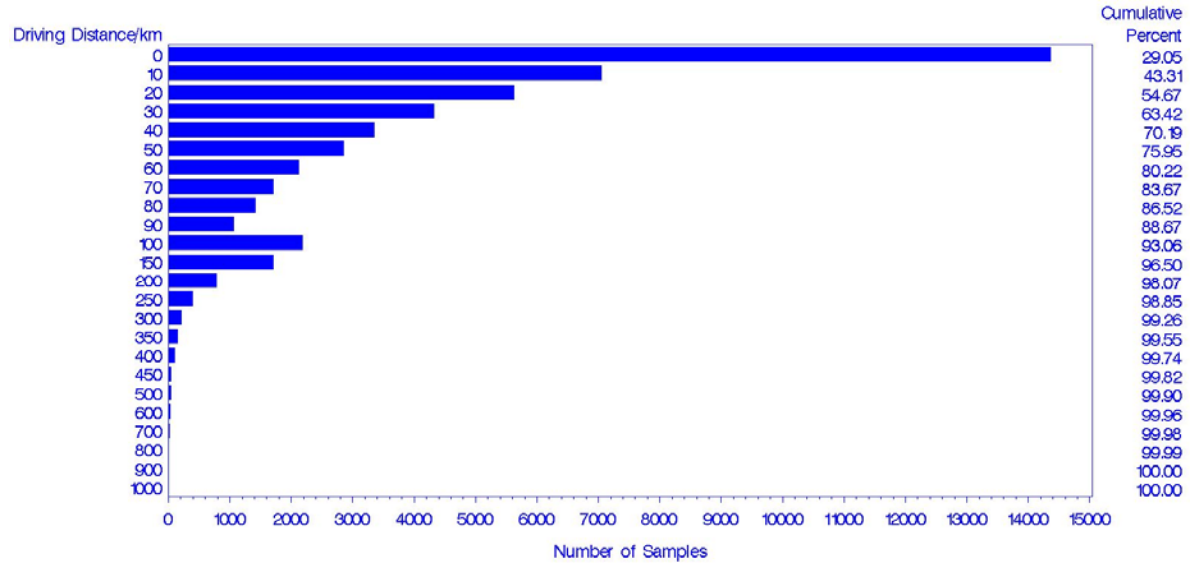

Figure 2-3 Cumulative Driving Distance Distribution in Denmark

In the TU data, the start and ending time of all parking time periods from one respondent were combined to determine the time periods which are available for EV charging and discharging. From the parking time periods of one respondent, the availability and unavailability of the EV for this respondent were determined. The time periods between the parking time periods were specified as unavailability time periods. From the raw data, the availability or unavailability of each minute was determined. Afterwards, the Hour Availability data were calculated based on the minute data.

The overall EV hour availability (All-Day) is illustrated in Figure 2-4. The result in Figure 2-4 shows that the EV availability is quite high if only the driving time periods are considered as the unavailable periods. The EV availability is on a very high plateau close to 100% during the early morning until 7 am. The EV availability is in the range of 93% to 97% during the day time from 7 am to 6 pm. During night from 7 pm to 3 am the next day, the EV availability rises gradually from 96% to near 100%.

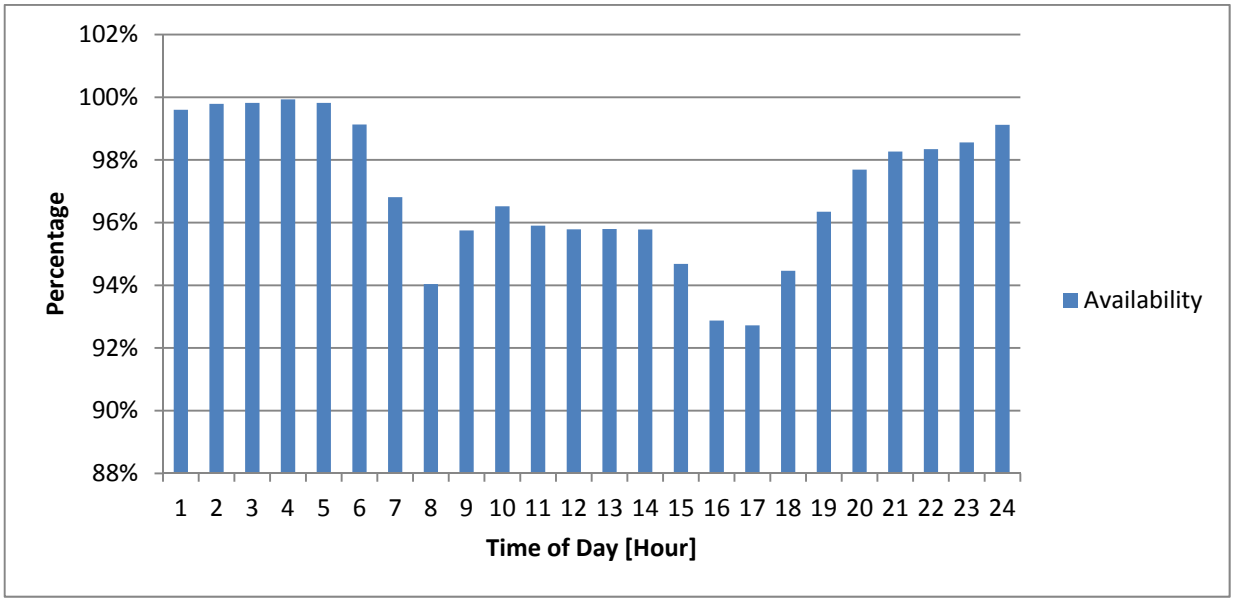

Figure 2-4 Overall EV Hour Availability Data (All-Day) in Denmark

It is worth to note that the EV availability patterns are different by far between weekdays and weekends. The EV hour availability of weekdays, Saturday and Sunday is illustrated in Figure 2-5. The EV hour availability on weekends is a little bit higher than the one on weekdays in general. On weekdays, the EV availability drops in the morning when people are supposed to leave home for work, and at 7-8 am the EV availability reaches a trough with about 92%. In the evening, there is another valley of the EV availability from 3 pm to 7 pm when people are supposed to leave the working places for home. After that, the availability increase constantly to near 100% in the midnight. During the weekends, the EV availability decreases gradually during the morning and climbs up again from the afternoon to the midnight.

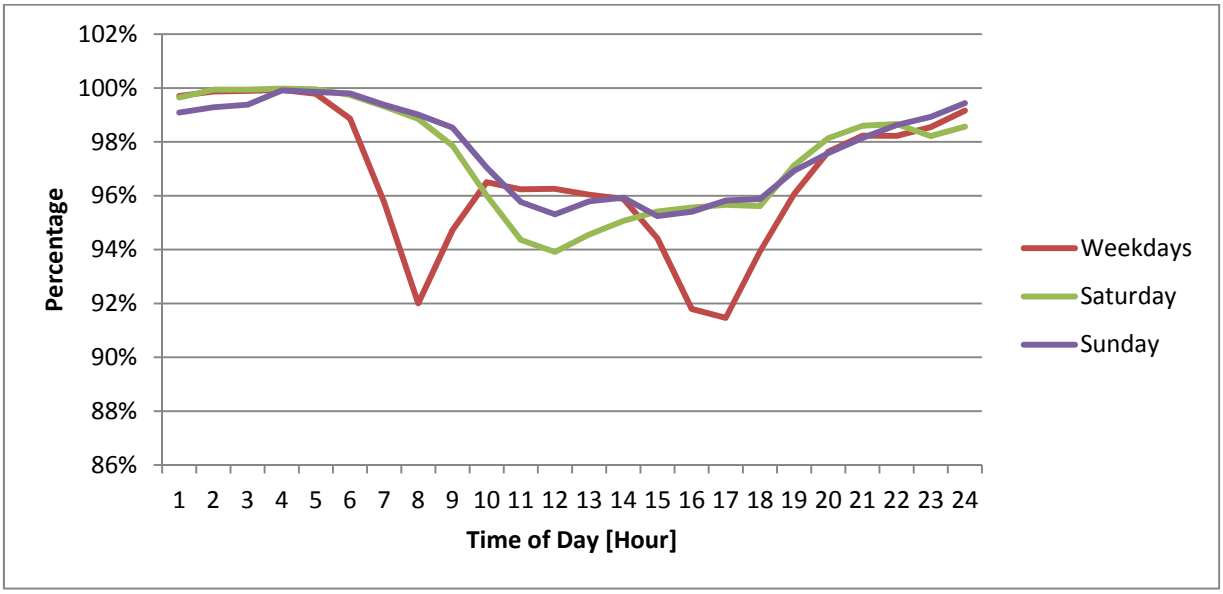

Figure 2-5 Hour Availability Data (All-Day) of Weekdays, Saturday and Sunday in Denmark

The EV Hour availability with the vehicles are parked at home is illustrated in Figure 2-6 and Figure 2-7.

The EV availability (At-Home) with vehicle can only be charged at home is much lower than the EV availability (All-Day). The availability drops to around 54% in the middle of the day and rises up steadily from the afternoon until the night. As shown in Figure 2-7 the EV availability on weekdays drops in the morning and rises obviously in the evening while the EV availability curves are more gentle on weekends. Furthermore, the overall availability of weekends is obviously higher than that of weekdays in general in Denmark.

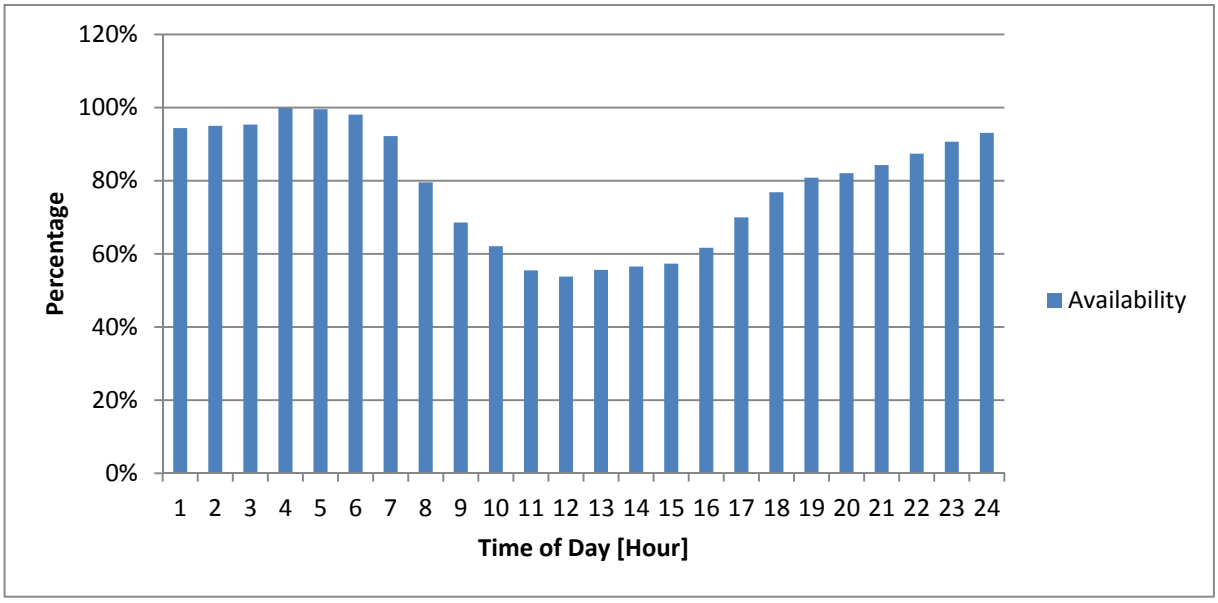

Figure 2-6 Overall EV Hour Availability Data (At-Home) in Denmark

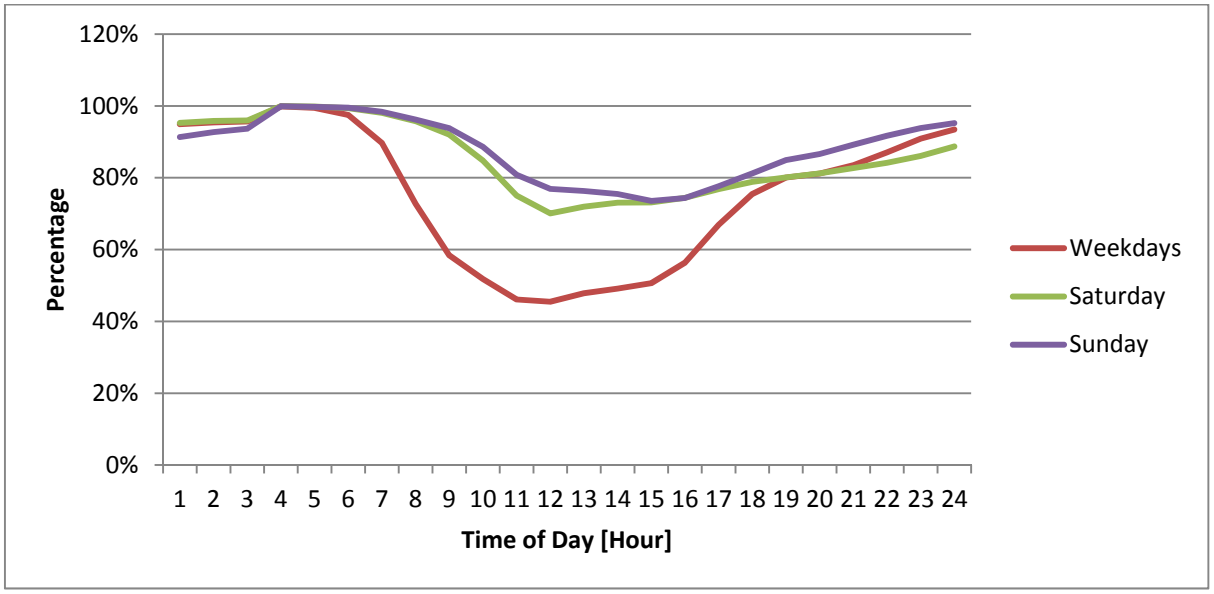

Figure 2-7 Hour Availability Data (At-Home) of Weekdays, Saturday and Sunday in Denmark

2.3 Driving Pattern Analysis in Sweden

The annual average driving distance of passenger cars in Sweden is about 11680km [3]. In order to be consitent with this figure, a coefficent of 0.85 is applied on the driving distance data from the Swedish National Travel Survey during the analysis. The average driving distance data are listed in Table 2-3. The overall average daily driving distance is about 32km. The difference of the average driving distance between weekdays and weekends is not large. In 2011, the number of passenger cars in Sweden is 3.75 millions [3].

Table 2-3 Average Driving Distance Data in Sweden

Day Type	Average Driving Distance [km]
All days	32.0
Weekdays	32.5
Saturday	30.5
Sunday	30.6

The individual and cumulative driving distance distributions are illustrated in Table 2-4, Figure 2-8 and Figure 2-9 respectively. It is shown that about 77.5% of the passenger cars have a daily driving distance of 45km or less.

Table 2-4 Driving Distance Distribution in Sweden

Driving Distance [km]	Individual [%]	Cumulative [%]
0	51.42	51.42
10	9.51	60.94
20	7.05	67.99
30	4.19	72.18
40	5.32	77.50
50	4.26	81.76
60	3.27	85.03
70	2.53	87.56
80	1.94	89.51
90	1.93	91.44
100	2.82	94.27
150	2.55	96.82
200	1.14	97.96
250	0.59	98.54
300	0.38	98.93
350	0.24	99.17
400	0.21	99.38
450	0.17	99.55
500	0.10	99.65
600	0.18	99.82
700	0.12	99.94
800	0.02	99.96
900	0.00	99.96
1000	0.04	100.00

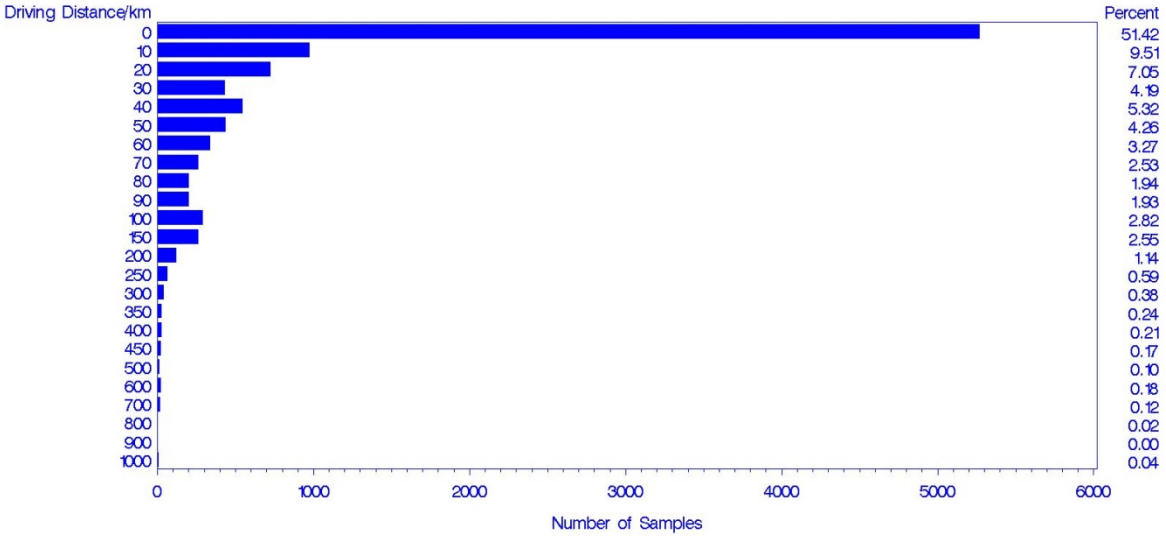

Figure 2-8 Individual Driving Distance Distribution in Sweden

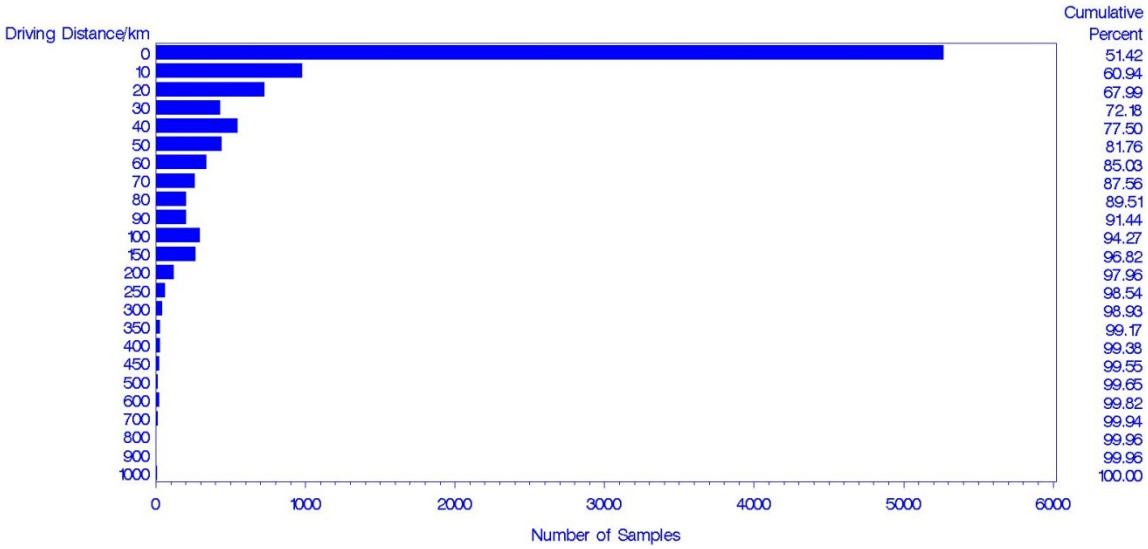

Figure 2-9 Cumulative Driving Distance Distribution in Sweden

The overall EV hour availability (All-Day) is illustrated in Figure 2-10. It shows the EV availability when only the driving time periods are considered as the unavailable periods. Under such assumption, the EV availability in Sweden is considerably high for over 90% throughout the day. The EV availability is in the range from around 90% to 96% during day time from 7 am to 6 pm. During the night from 6 pm to the night, the EV availability rises gradually to about 100%.

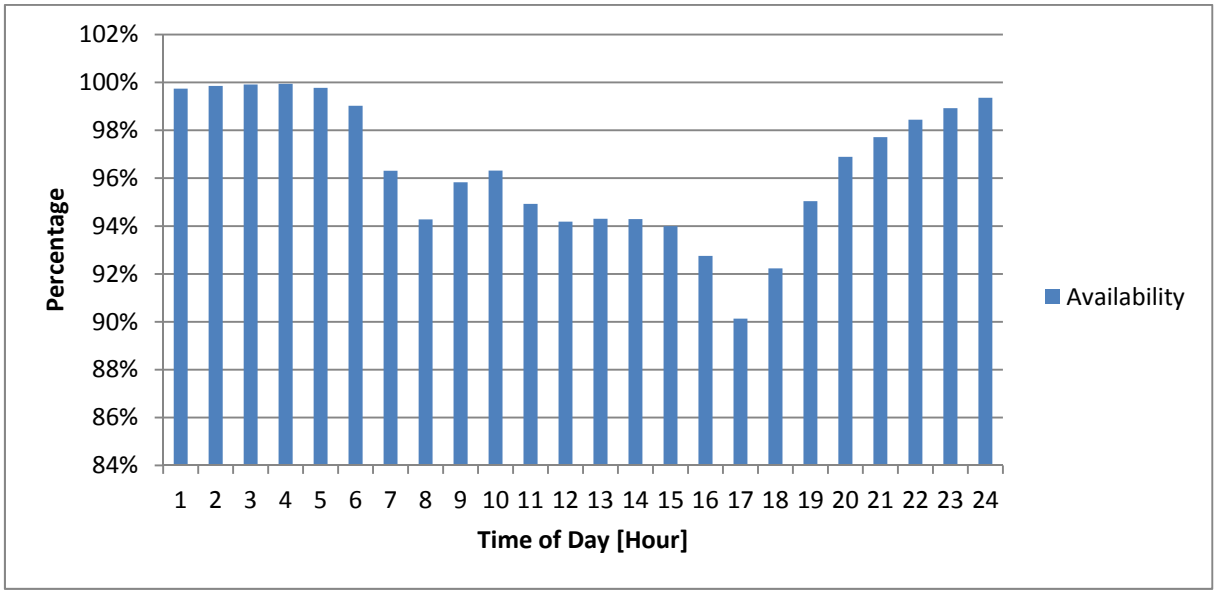

Figure 2-10 Overall EV Hour Availability Data (All-Day) in Sweden

It is worth to note that the EV availability patterns are different in Sweden between weekdays and weekends. The EV hour availability of weekdays, Saturday and Sunday is illustrated in Figure 2-11. On weekdays, the EV availability drops in the morning when people are supposed to leave home for work, and at 7-8 am the EV availability reaches a trough slight above 92%. In the evening, there is another valley of the EV availability from 3 pm to 7 pm when people are supposed to leave the working places for home. After that the availability increase constantly to near 100% in the midnight. On weekends, the EV availability decreases gradually during the morning and climbs up again from the evening to the midnight.

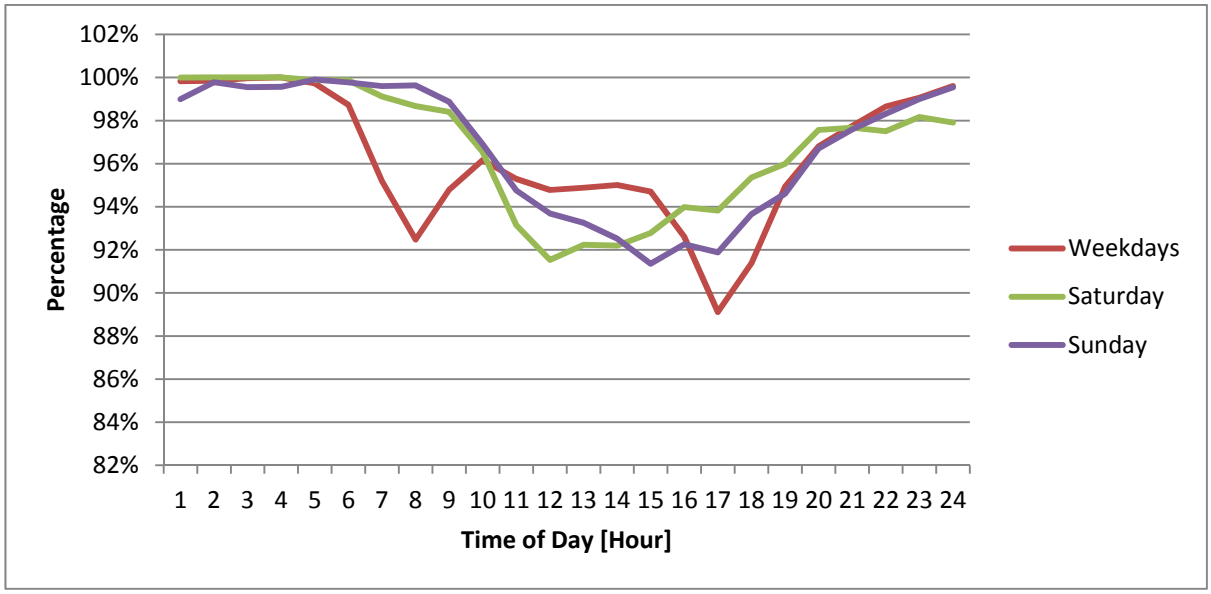

Figure 2-11 Hour Availability Data (All-Day) of Weekdays, Saturday and Sunday in Sweden

The EV Hour availability with the vehicles are parked at home is illustrated in Figure 2-12 and Figure 2-13.

The EV availability (At-Home) with vehicle can only be charged at home is much lower than the EV availability (All-Day). The availability drops to around 54% in the middle of the day and rises up steadily from the afternoon until the night. As shown in Figure 2-13 the EV availability on weekdays drops in the morning and rises obviously in the evening while the EV availability curves are more gentle on weekends. Furthermore, the overall availability of weekends is obviously higher than that of weekdays in general in Sweden.

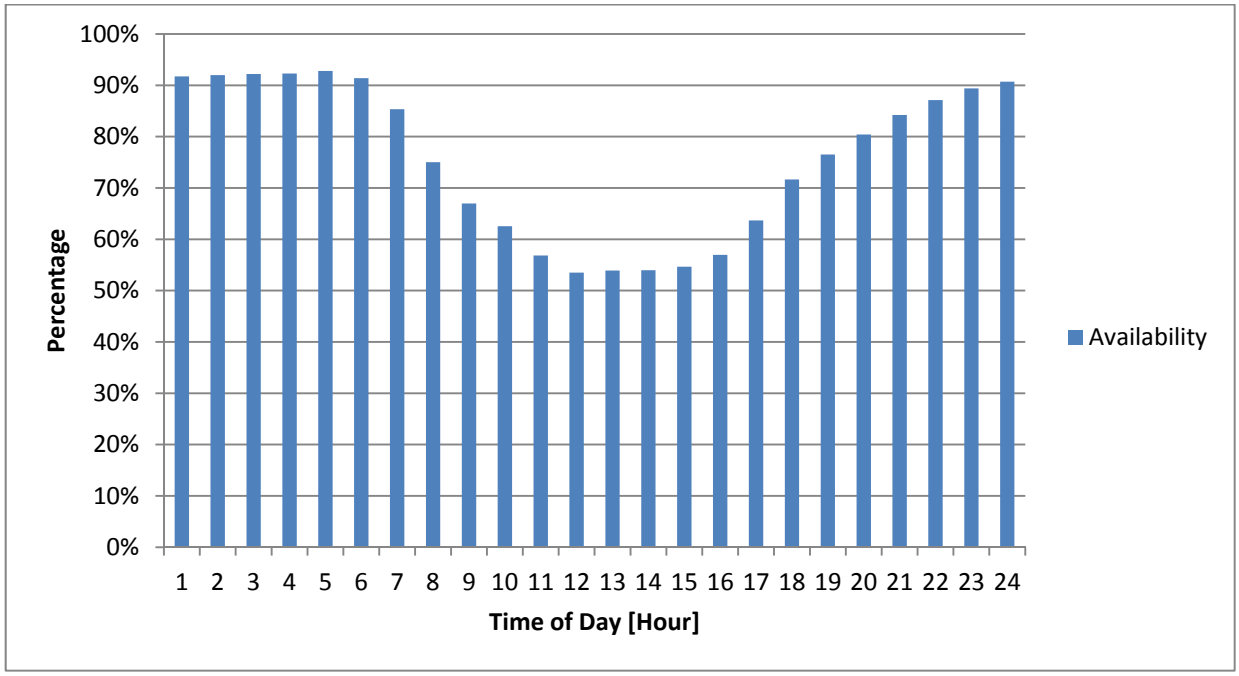

Figure 2-12 Overall EV Hour Availability Data (At-Home) in Sweden

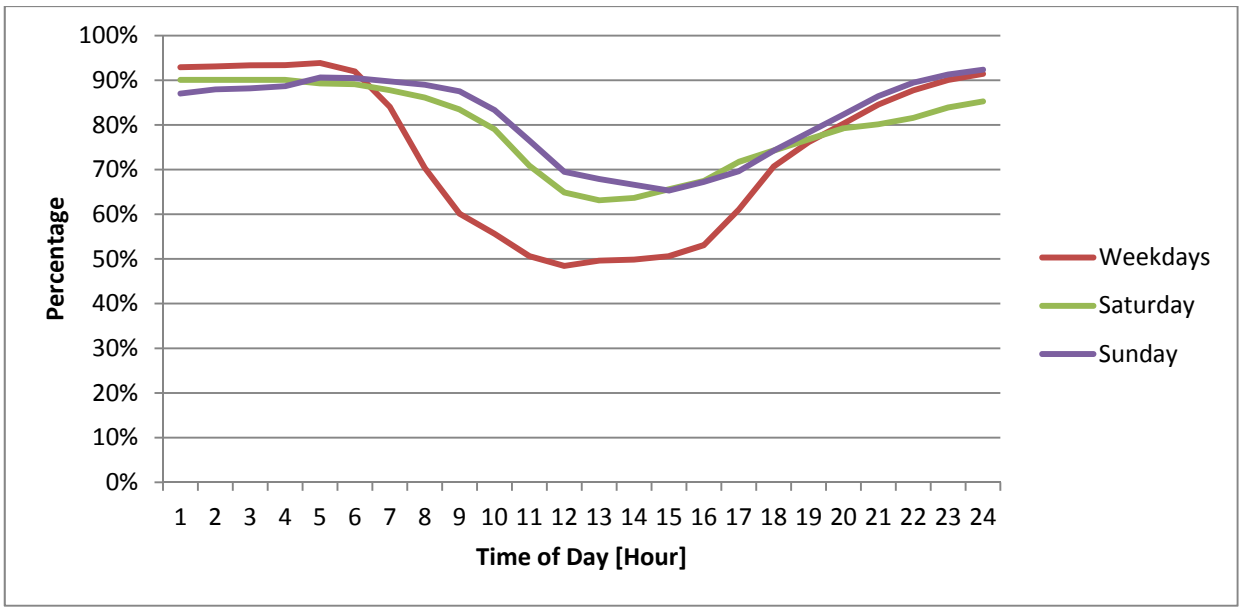

Figure 2-13 Hour Availability Data (At-Home) of Weekdays, Saturdays and Sundays in Sweden

2.4 Driving Pattern Analysis in Norway

The annual average driving distance of passenger cars in Norway is about 12985km [4]. In order to be consitent with this figure, a coefficent of 1.08 is applied on the driving distance data from the Norwegian National Travel Survey in the analysis. The average driving distance of passenger cars in Norway is shown in Table 2-5. The overall average daily driving distance is about 36km. In 2011, the number of the registered private cars in Norway is 2.38 millions [5].

Table 2-5 Average Driving Distance Data in Norway

Day Type	Average Driving Distance [km]
All days	35.6
Weekdays	36.6
Saturday	32.3
Sunday	33.6

The individual and cumulative driving distance distributions are illustrated in Table 2-6, Figure 2-14 and Figure 2-15 respectively. It is shown that about 77.2% of the passenger cars have a daily driving distance of 45km or less.

Table 2-6 Driving Distance Distribution of Weekdays in Norway

Driving Distance [km]	Individual [%]	Cumulative [%]
0	43.39	43.39
10	13.44	56.83
20	9.13	65.96
30	5.93	71.88
40	5.31	77.19
50	3.87	81.06
60	3.14	84.20
70	2.38	86.58
80	1.40	87.98
90	1.66	89.64
100	3.60	93.23
150	2.55	95.78
200	1.63	97.41
250	0.89	98.31
300	0.53	98.84
350	0.40	99.24
400	0.22	99.46
450	0.19	99.65
500	0.11	99.76
600	0.09	99.85
700	0.08	99.93
800	0.02	99.95
900	0.02	99.97
1000	0.03	100.00

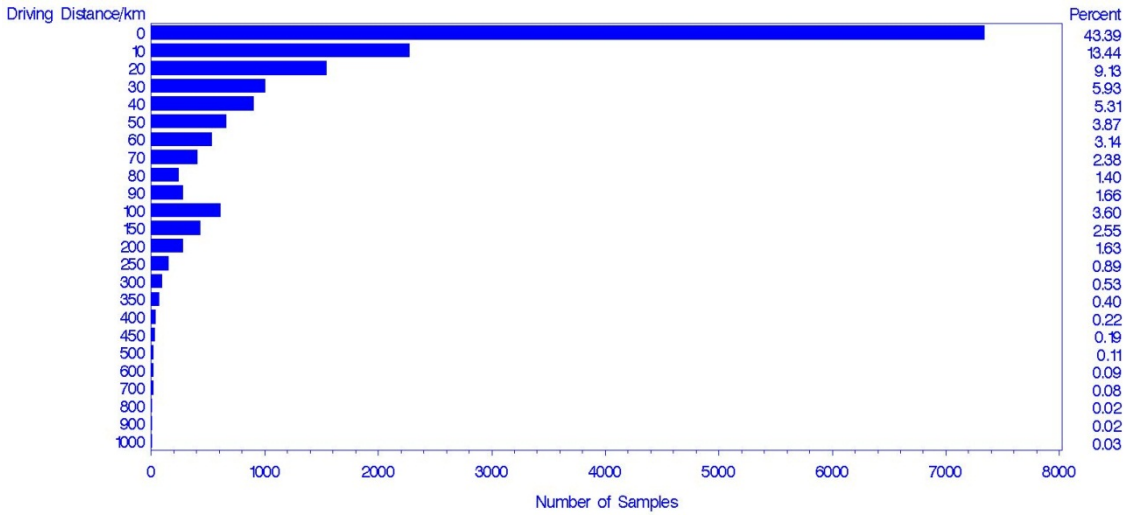

Figure 2-14 Individual Driving Distance Distribution in Norway

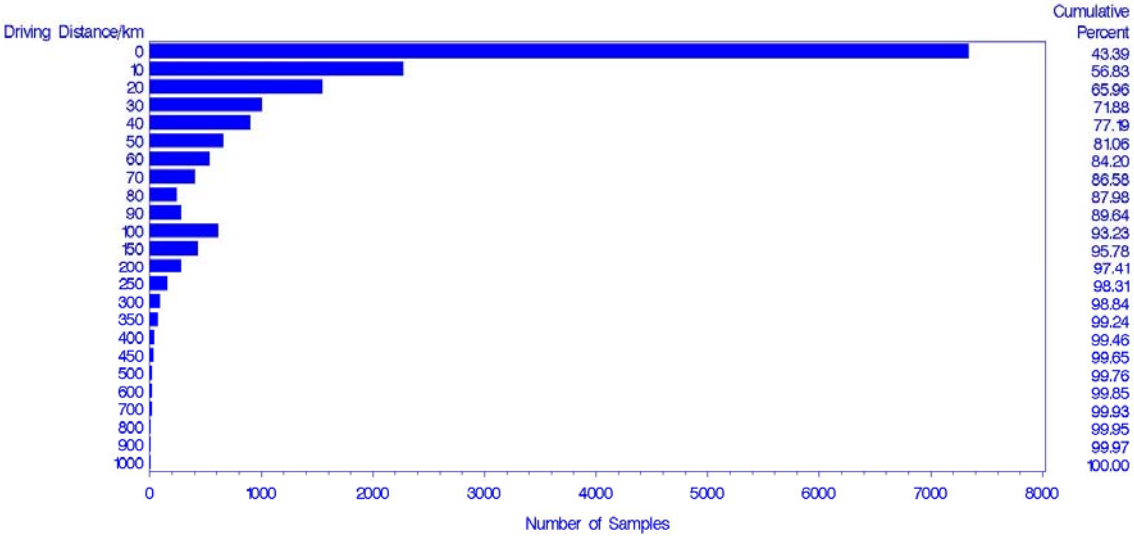

Figure 2-15 Cumulative Driving Distance Distribution in Norway

The overall EV hour availability of one day is illustrated in Figure 2-16.

Figure 2-16 shows the EV availability (All-Day) when only the driving time periods are considered as the unavailable periods. Under such assumption, the EV availability in Norway is considerably high for over 92% throughout the day. The EV availability is in the range of around 92% to 98% during day time from 7 am to 6 pm. During night from 7 pm, the EV availability rises gradually to near 100% at midnight.

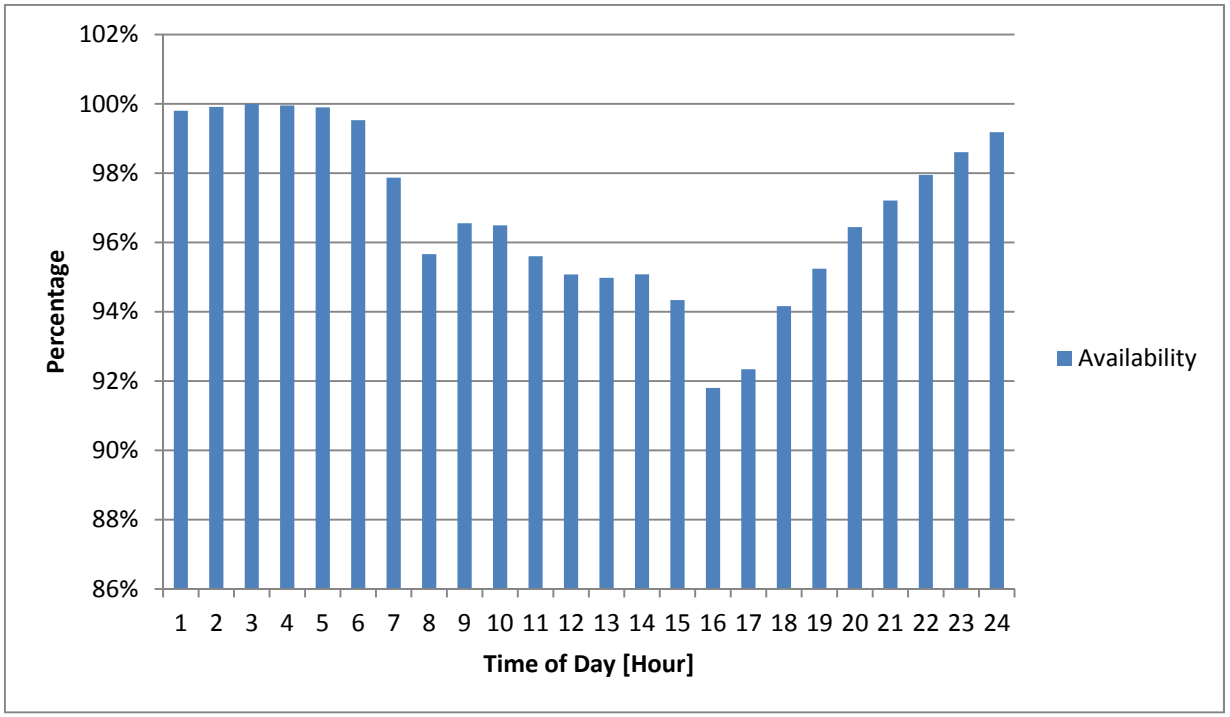

Figure 2-16 Overall EV Hour Availability Data (All-Day) in Norway

The EV hour availability of Weekdays, Saturdays and Sundays is illustrated in Figure 2-17.

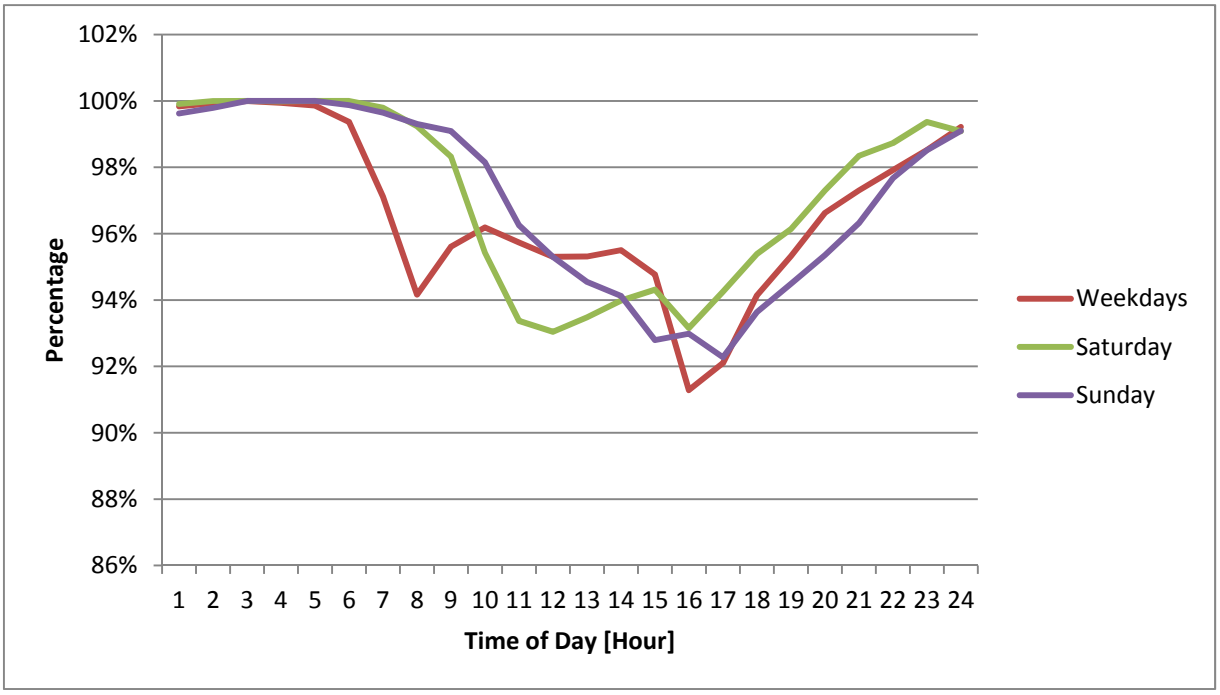

Figure 2-17 Hour Availability Data (All-Day) of Weekdays, Saturday and Sunday in Norway

The EV Hour availability (At-Home) is illustrated in Figure 2-18 and Figure 2-19.

The EV availability (At-Home) with vehicle can only be charged at home is much lower than the EV availability (All-Day) in the day time. The availability drops to around 58% in the middle of the day and rises up steadily from the afternoon until the night. As shown in Figure 2-19 the EV availability on weekdays drops in the morning and rises obviously in the evening while the EV availability curves are more gentle on weekends. The overall availability of weekends is obviously higher than that of weekdays in general.

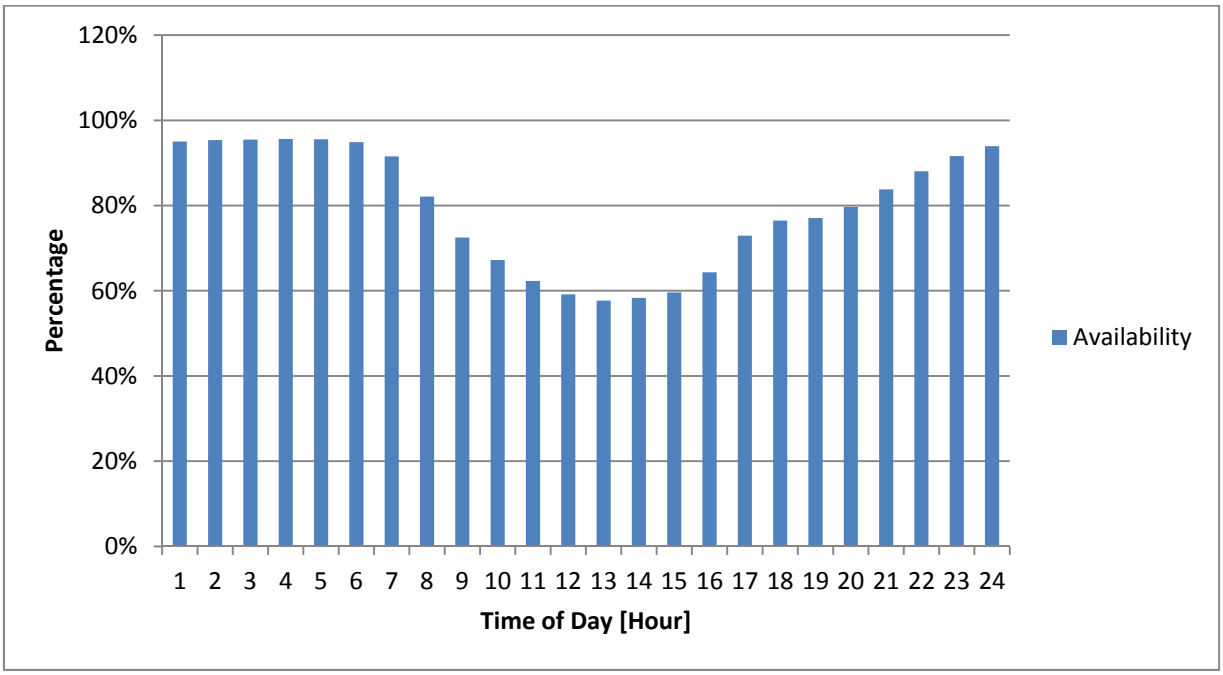

Figure 2-18 Overall EV Hour Availability Data (At-Home) in Norway

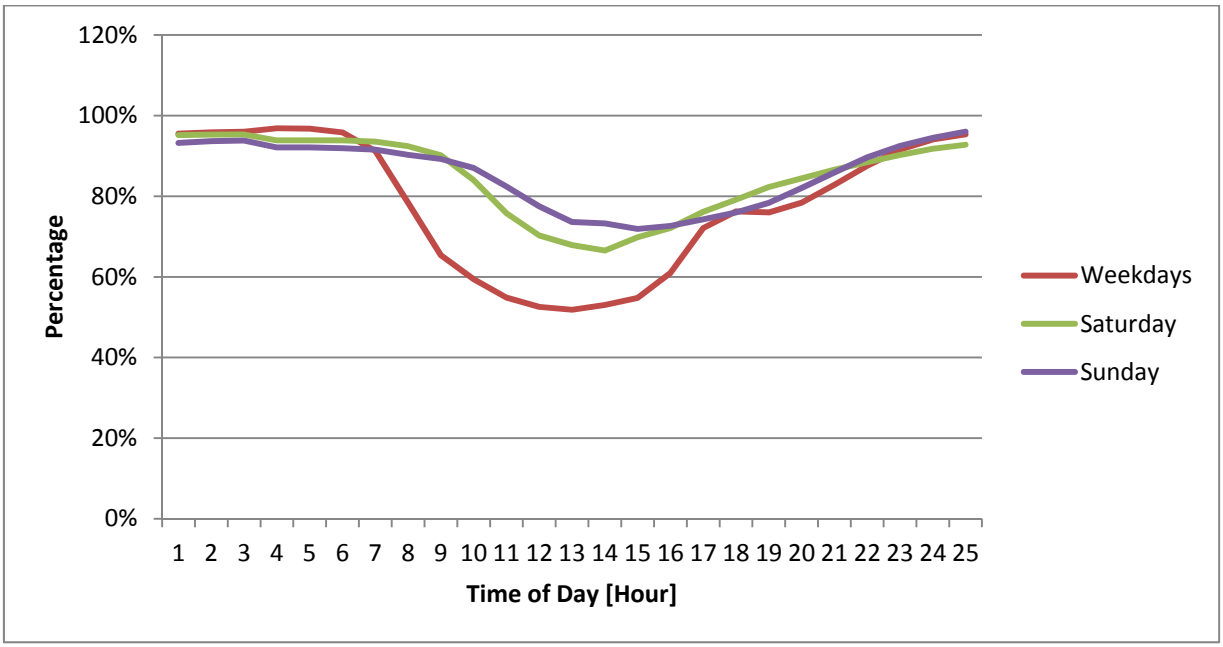

Figure 2-19 Hour Availability Data (At-Home) of Weekdays, Saturday and Sunday in Norway

2.5 Driving Pattern Analysis in Finland

The annual average driving distance of passenger cars in Finland is about 17085km [6]. In order to be consitent with this figure, a coefficent of 1.05 is applied on the driving distance data from the Finnish National Travel Survey in the analysis. The average driving distance of passenger cars in Finland is shown in Table 2-7. The overall average daily driving distance is about 47km. In Finland, the number of registered passenger cars is 2.98 millions in 2011 [7].

Table 2-7 Average Driving Distance Data in Finland

Day Type	Average Driving Distance [km]
All days	46.8
Weekday	45.3
Saturday	47.0
Sunday	55.2

The individual and cumulative driving distance distributions are illustrated in Table 2-8, Figure 2-20 and Figure 2-21 respectively. It is shown that about 69.7% of the passenger cars have a daily driving distance of 45km or less.

Table 2-8 Driving Distance Distribution of Weekdays in Finland

Driving Distance [km]	Individual [%]	Cumulative [%]
0	34.84	34.84
10	12.58	47.41
20	9.34	56.75
30	6.89	63.64
40	6.04	69.68
50	4.87	74.55
60	3.78	78.33
70	3.21	81.54
80	2.62	84.16
90	1.79	85.95
100	4.41	90.36
150	3.73	94.09
200	2.14	96.23
250	1.22	97.45
300	0.80	98.25
350	0.62	98.87
400	0.25	99.12
450	0.25	99.37
500	0.25	99.62
600	0.10	99.72
700	0.14	99.86
800	0.10	99.96
900	0.00	99.96
1000	0.04	100.00

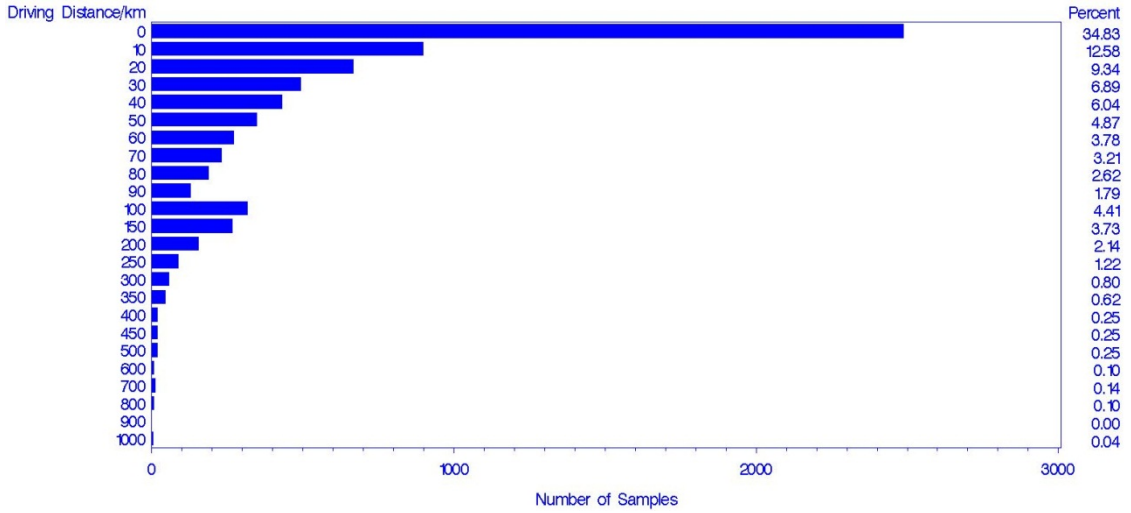

Figure 2-20 Individual Driving Distance Distribution in Finland

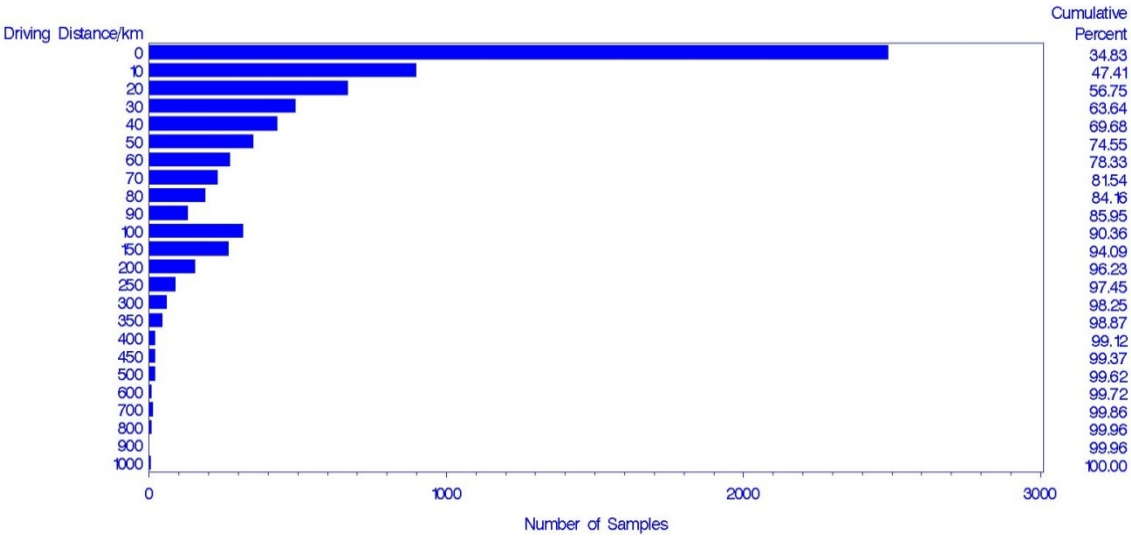

Figure 2-21 Cumulative Driving Distance Distribution in Finland

The overall EV hour availability (All-Day) is illustrated in Figure 2-22.

Figure 2-22 shows the EV availability (All-Day) when only the driving time periods are considered as the unavailable periods. Under such assumption, the EV availability in Finland is considerably high for over 91% throughout the day. The EV availability is in the range of around 91% to 95% during day time from 8 am to 6 pm. From 7 pm to midnight, the EV availability rises gradually from about 94% to near 100%.

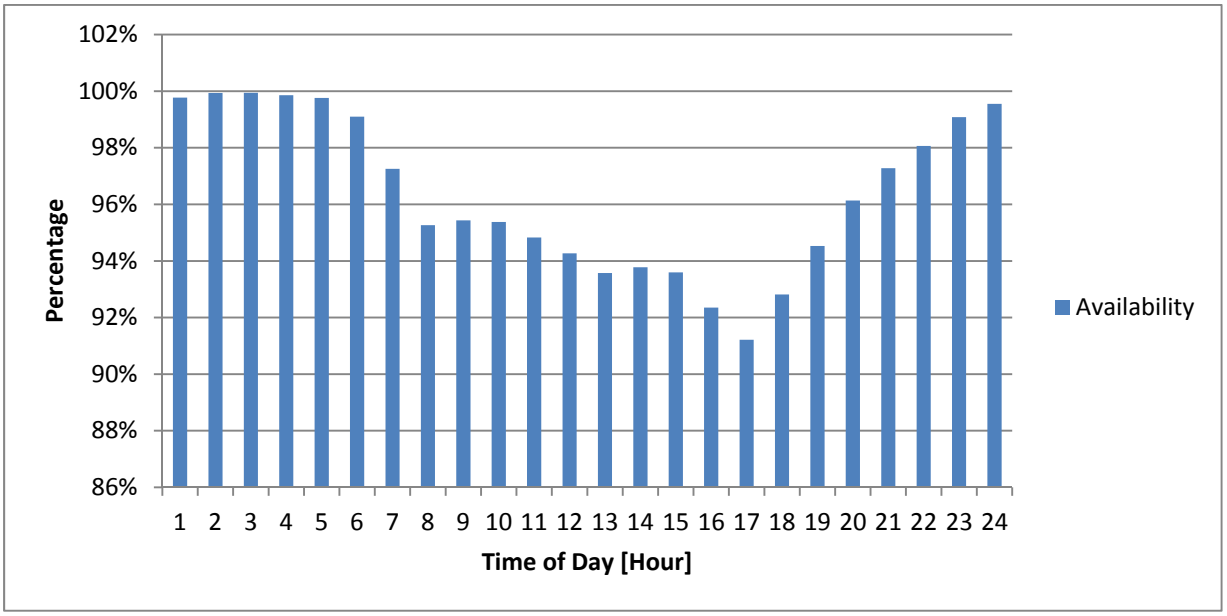

Figure 2-22 Overall EV Hour Availability Data (All-Day) in Finland

The EV availability patterns (All-Day) is different between weekdays and weekends. The EV hour availability of weekdays, Saturday and Sunday is illustrated in Figure 2-23. On weekdays, the EV availability drops in the morning when people are supposed to leave home for work, and at 7-8 am the EV availability reach a trough with about 94%. In the evening, the EV availability reaches the lowest point slightly above 91% at 4-6 pm when people are supposed to leave the working places for home. After that the availability increase constantly to near 100% at midnight. On weekends, the EV availability decreases gradually during the morning and climbs up again from the evening to the night.

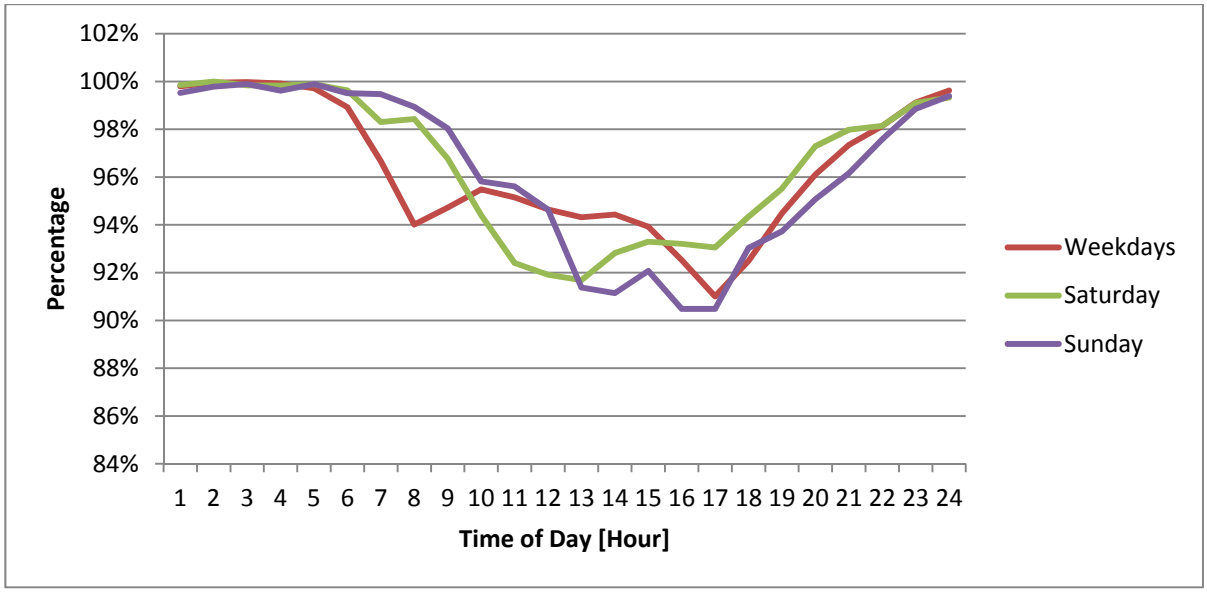

Figure 2-23 Hour Availability Data (All-Day) of Weekdays, Saturday and Sunday in Finland

The EV Hour availability (At-Home) is illustrated in Figure 2-24 and Figure 2-25.

The EV availability (At-Home) with vehicle can only be charged at home is much lower than the EV availability (All-Day). The availability drops to around 60% in the middle of the day and rises up steadily from the afternoon until the night. As shown in Figure 2-25 the EV availability on weekdays drops in the morning and rises obviously in the evening while the EV availability curves are more gentle on weekends. Furthermore, the overall availability of weekends is obviously higher than that of weekdays in general in Finland.

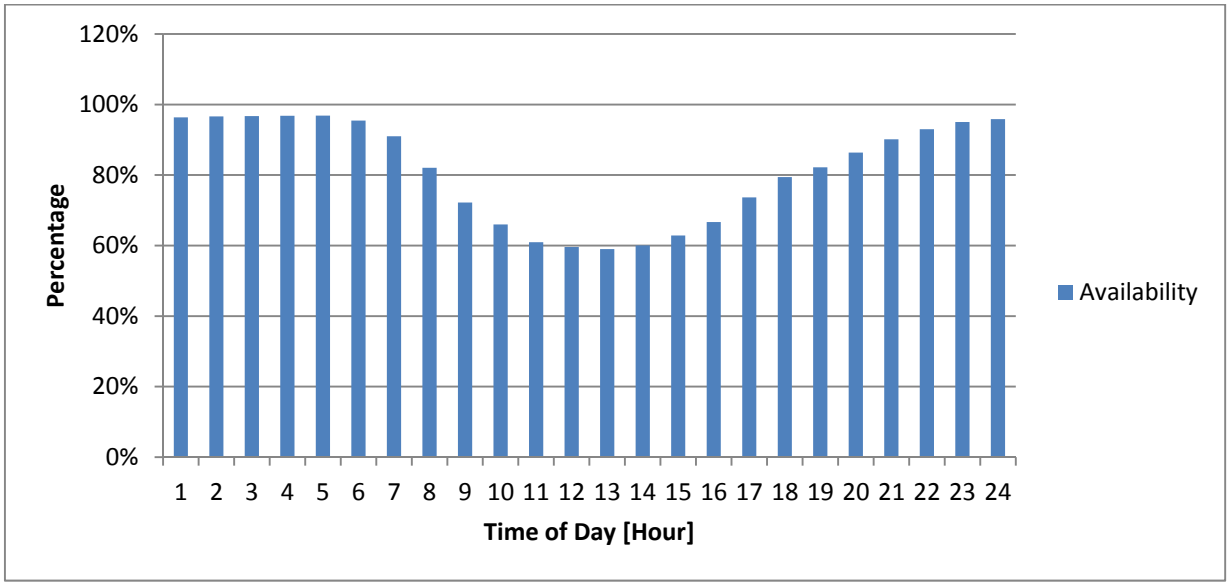

Figure 2-24 Overall EV Hour Availability Data (At-Home) in Finland

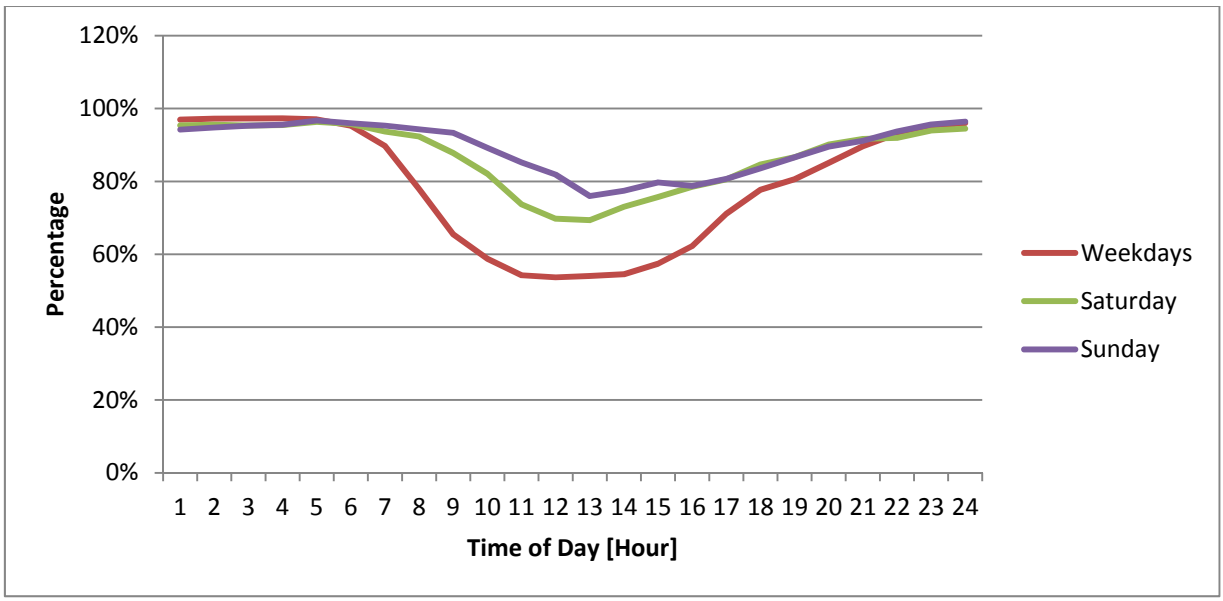

Figure 2-25 Hour Availability Data (At-Home) of Weekdays, Saturday and Sunday in Finland

2.6 Summary

The driving patterns of passenger cars in Denmark, Sweden, Norway and Finland are studied in this chapter. The driving pattern studies are based on the National Travel Surveys of the four countries. Table 2-9 shows the average driving distance of the passenger cars per day in the Nordic region. The daily average driving distances of all the four countries are in a reasonable range compared to the endurance of EVs with current technologies. The Finnish case has the longest average driving distance while this number in Sweden shows to be the lowest of all. Most of the daily trips in the Nordic region are in a relatively short distance. Table 2-10 indicates the percentages of passenger cars with the daily driving distance within 45km. It is shown that the majority of the passenger cars in the four mentioned Nordic countries have a daily driving distance in the low-distance range.

Table 2-9 Daily Average Driving Distance in the Nordic Region

Denmark [km]	Sweden [km]	Norway [km]	Finland [km]
40.2	32.0	35.6	46.8

Table 2-10 Percentages of Daily Driving Distance within 45km in the Nordic Region

Denmark	Sweden	Norway	Finland
70.4%	77.5%	77.2%	69.7%

The EV charging availability has similar patterns for all the four mentioned Nordic countries. Furthermore, the EV charging availability on weekdays shows to be different significantly from that on weekends. For the EV charging availability (All-Day) when only the driving periods are considered as the unavailable periods, it shows to be on a relatively high level for over 90% throughout the day. During the weekdays, there are two notable valleys in the morning and in the evening when people are supposed to leave for work and go home. However, the EV availability on weekends has a more gentle shape than that on weekdays. It decreases gradually during the morning and ascends again from the afternoon to the midnight.

If the EVs are supposed to only be charged at home, the patterns of the availability show to be different markedly. The EV availability (At-Home) is much lower than EV availability (All-Day) when the EVs can be charged regardless of the parking spot. On weekdays, the EV availability (At-Home) begins to decrease in the morning when people start to leave home for work, keeps on a low level during the day time and increases again in the afternoon when people start to go home. The differences between the EV availability (All-Day) and EV availability (At-Home) can have an impact on the EV charging load depending on the charging patterns, which will be investigated in chapter 3.

3 EV Charging Analysis of the Nordic Region

Based on the driving pattern analysis of the Nordic region in chapter 2, the EV charging analysis of the Nordic region is implemented. The goal of the EV charging analysis is to investigate the electrical load patterns of different EV charging strategies with different charging rates when or if there is a high penetration level of EVs in Denmark, Sweden, Norway and Finland. In the charging analysis, five different types of EV charging patterns are studied including dumb charging all day, dumb charging at home, timed charging, spot price based charging all day and spot price based charging at home. The EV charging rates in the studies are selected typically as 2.3kW for 1 phase 10A charging, 3.68kW for 1 phase 16A charging and 11.04kW for 3 phase 16A charging. Afterwards, a summary on the EV charging studies is given in the end of this chapter.

3.1 Method of the EV Charging Analysis

The EV charging analysis is based on the driving pattern analysis of the Nordic region described in chapter 2. In the EV charging analysis, each vehicle is charged according to its own driving pattern with five different types of EV charging patterns, including dumb charging all day, dumb charging at home, timed charging, spot price based charging all day and spot price based charging at home. Here dumb charging all day refers to dumb charging whenever the studied vehicle is parked throughout the day; dumb charging at home refers to dumb charging when the studied vehicles is parked at home; timed charging refers to the charging that begins after 9:00 pm when the studied vehicle is parked; spot price based charging all day refer to the charging based on the spot price of the electrical market to minimize the daily charging cost whenever the studied vehicle is parked throughout the day; spot price based charging at home refer to the charging based on the spot price of the electrical market to minimize the daily charging cost when the studied vehicle is parked at home. The goal of all the different types of charging is to recover the energy consumption of the studied vehicle during the day.

Three different charging rates are applied typically in the charging analysis including 2.3kW for 1 phase 10A charging, 3.68kW for 1 phase 16A charging and 11.04kW for 3 phase 16A charging. With a certain charging pattern and a certain charging rate, the daily electrical charging curve of each vehicle is generated according to detailed driving pattern obtained from the driving pattern analysis in chapter 2. The electrical charging curves of all the studied vehicles are averaged to obtain the mean charging curves of one vehicle with different charging patterns and charging rates of the four mentioned Nordic countries respectively. The total EV charging curves of the four mentioned Nordic countries are generated by scaling up the mean charging curves with the passenger car numbers of the four countries respectively.

The time resolution of the EV charging analysis is in hour. The energy used per km for a home passenger car is typically between 120 Wh/km and 180 Wh/km [1]. In the charging analysis, an average energy consumption rate of 150 Wh/km is used to calculate the energy consumption of the studied vehicles.

3.2 Charging Analysis with High EV Penetration in Denmark

3.2.1 Dumb Charging Analysis

The electrical charging load curves of dumb charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-1 to Figure 3-3 respectively.

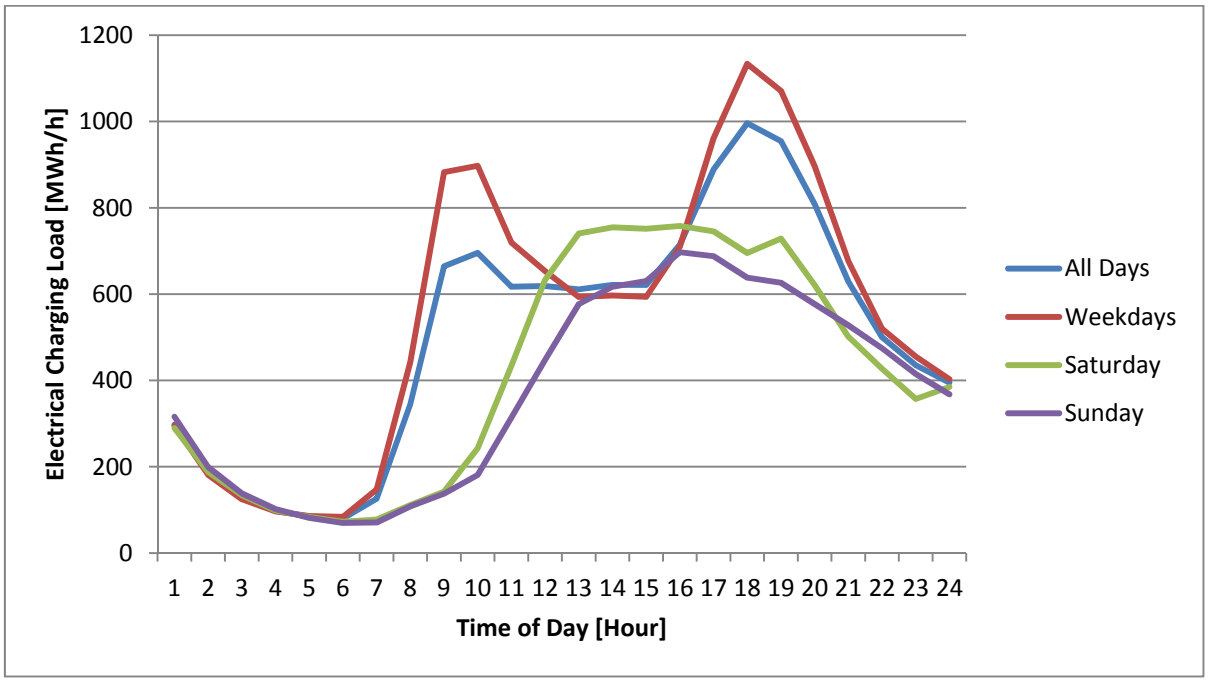

Figure 3-1 Electrical Load of 2.3kW Dumb Charging All Day in Denmark

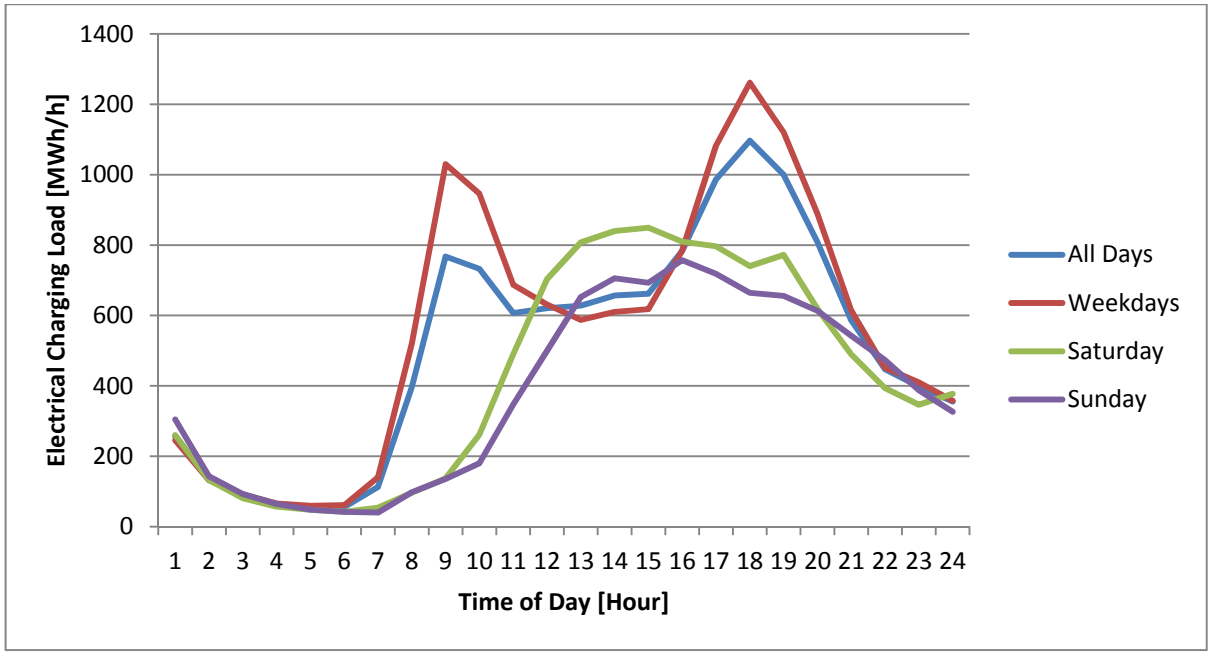

Figure 3-2 Electrical Load of 3.68kW Dumb Charging All Day in Denmark

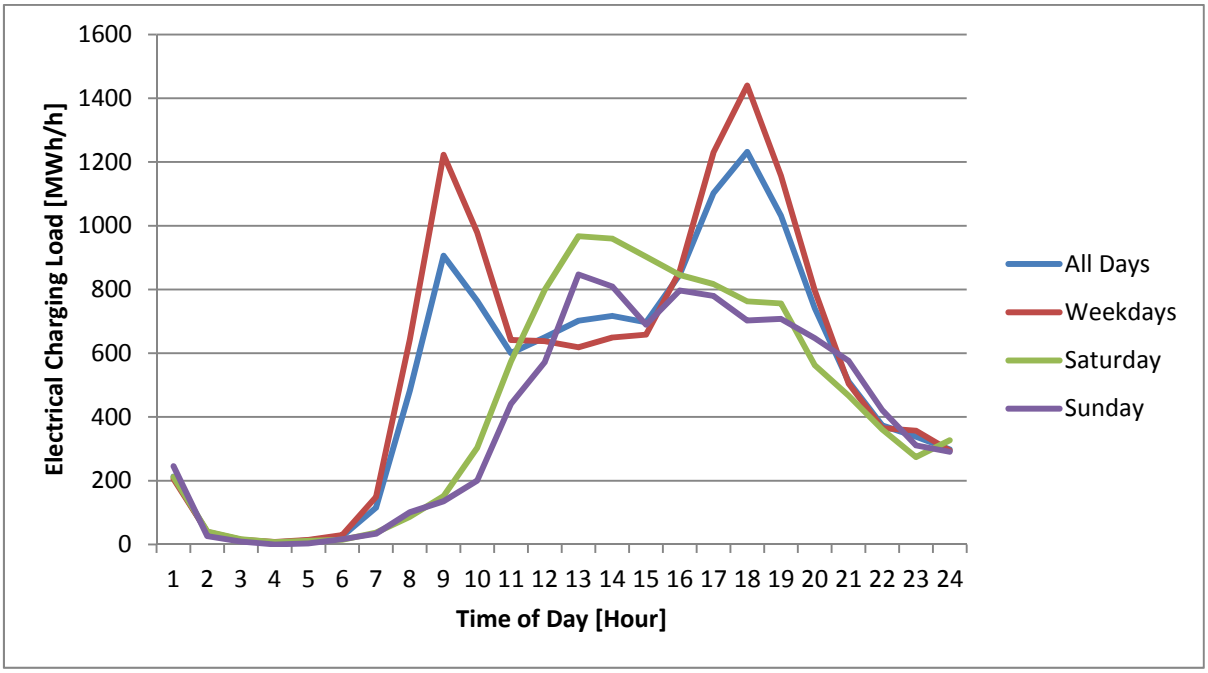

Figure 3-3 Electrical Load of 11.04kW Dumb Charging All Day in Denmark

During the weekdays, there are two spikes in the EV charging load curves of dumb charging all day in Denmark, one at 8-10 am in the morning and the other one at 5-8 pm in the evening. The highest load of the day appears at about 6 pm. The charging load on weekends rises late in the morning and the majority of the charging happens in the afternoon and evening. The charging load patterns are in accordance with the driving patterns of Denmark described in chapter 2.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-1 shows the peak electrical charging loads of dumb charging all day with different charging rates in Denmark.

Table 3-1 Peak Load of Dumb Charging All Day in Denmark

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.13	1.26	1.44
Saturday	0.76	0.85	0.97
Sunday	0.70	0.76	0.85

The electrical charging load curves of dumb charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-4 to Figure 3-6 respectively.

Different from the load of dumb charging all day, the load pattern of dumb charging at home has no spike in the morning on weekdays. The charging load starts to rise from around 3 pm in the afternoon and comes to the peak at about 6 pm when the most of the people are supposed to reach home from work.

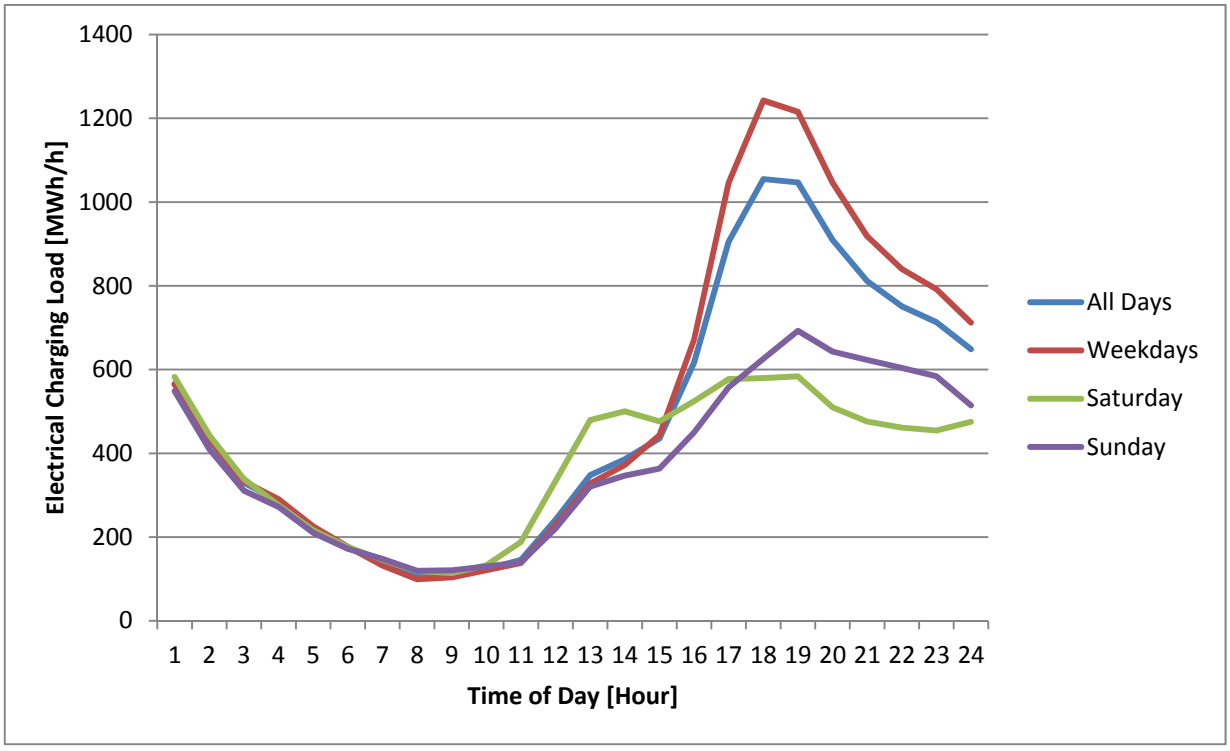

Figure 3-4 Electrical Load of 2.3kW Dumb Charging at Home in Denmark

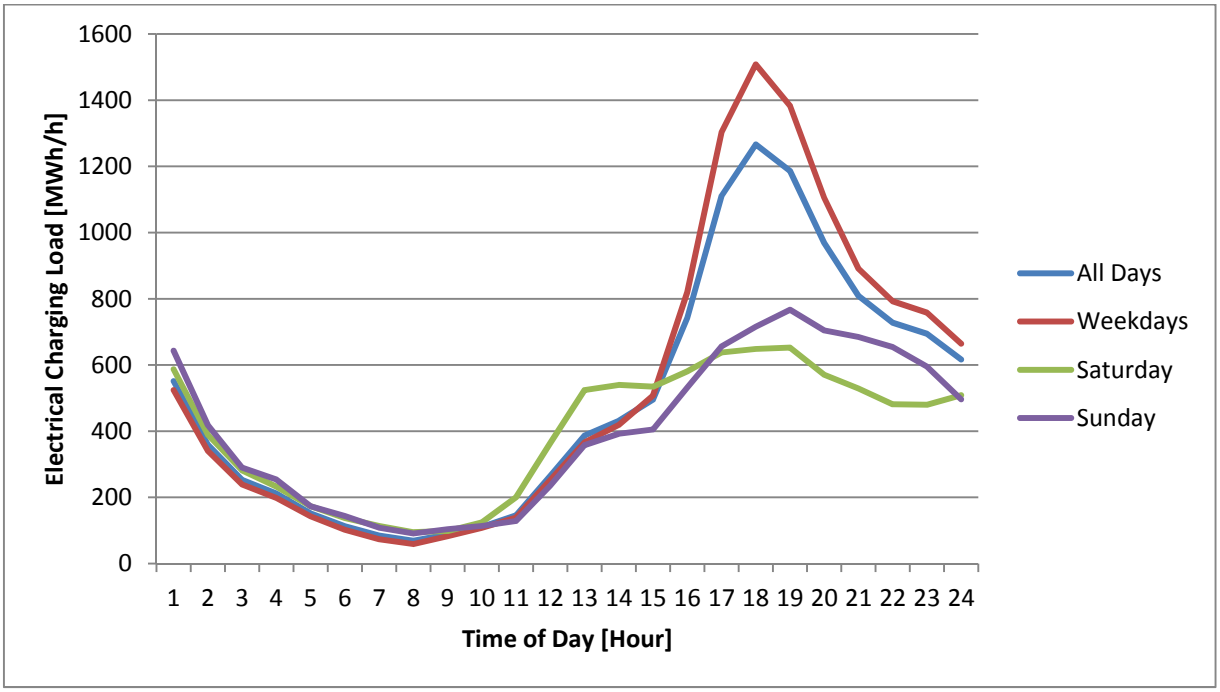

Figure 3-5 Electrical Load of 3.68kW Dumb Charging at Home in Denmark

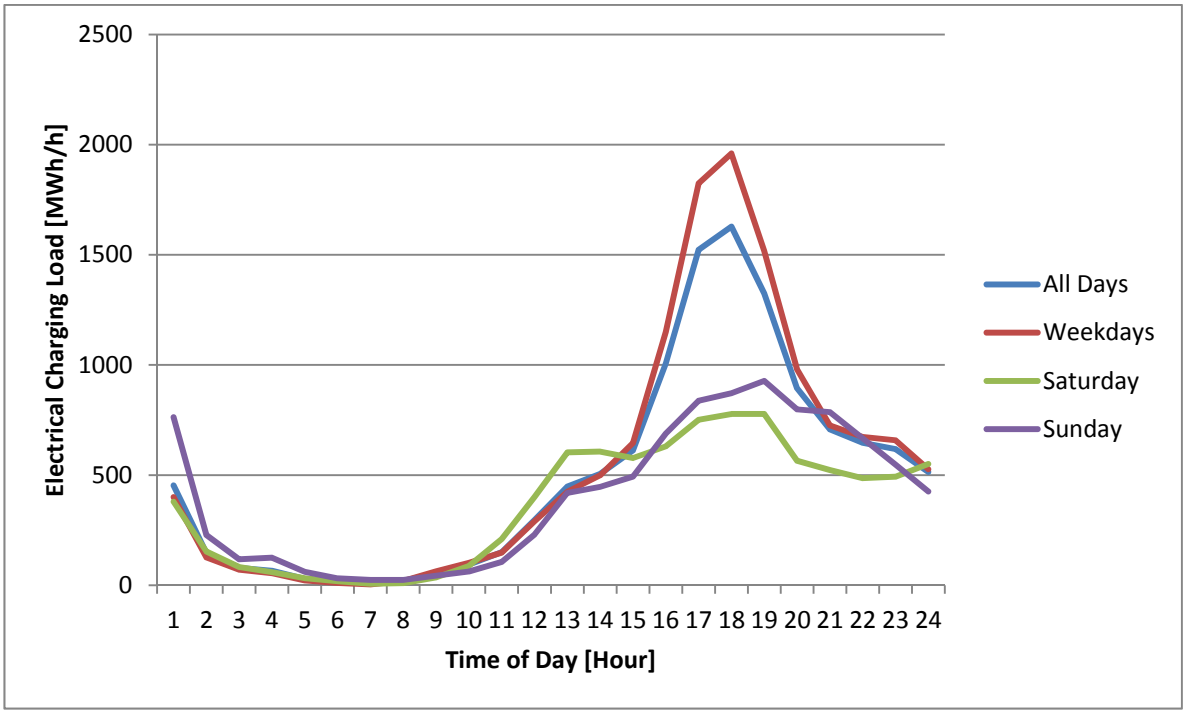

Figure 3-6 Electrical Load of 11.04kW Dumb Charging at Home in Denmark

Table 3-2 shows the peak electrical charging loads of dumb charging at home with different charging rates in Denmark. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-2 Peak Load of Dumb Charging at Home in Denmark

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.24	1.51	1.96
Saturday	0.58	0.65	0.78
Sunday	0.69	0.77	0.93

3.2.2 Timed Charging Analysis

The electrical charging load curves of timed charging that all vehicles are charged during the parking period after 9:00 pm with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-7 to Figure 3-9 respectively.

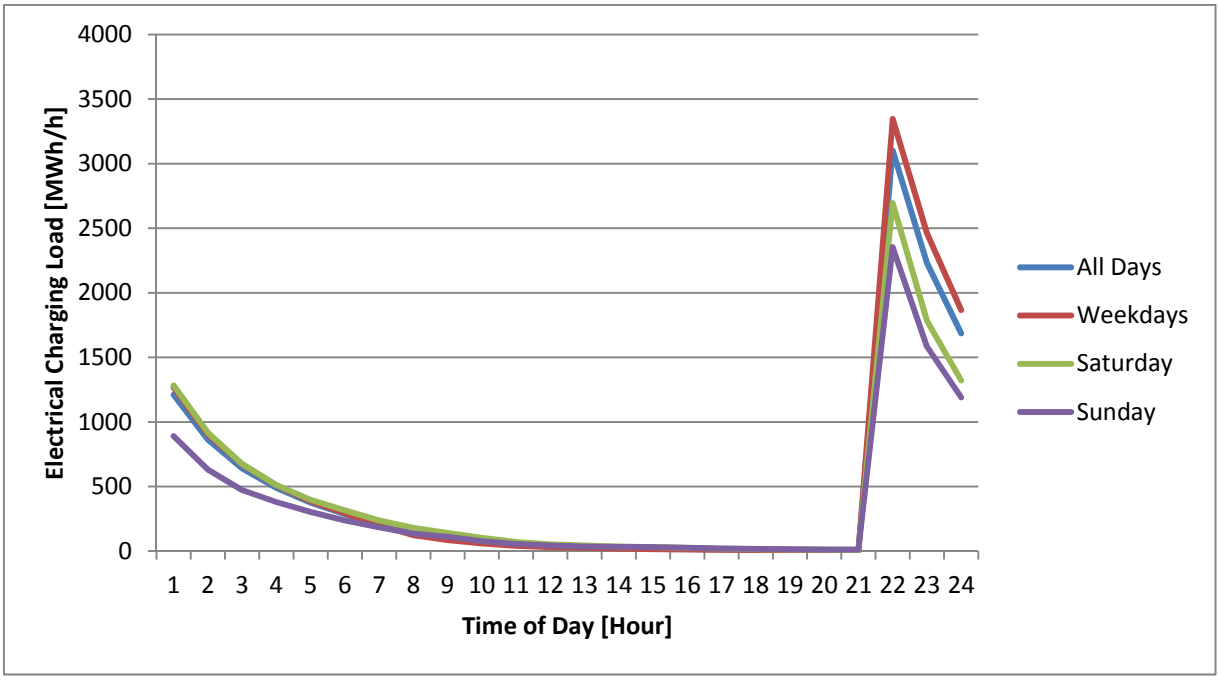

Figure 3-7 Electrical Load of 2.3kW Timed Charging in Denmark

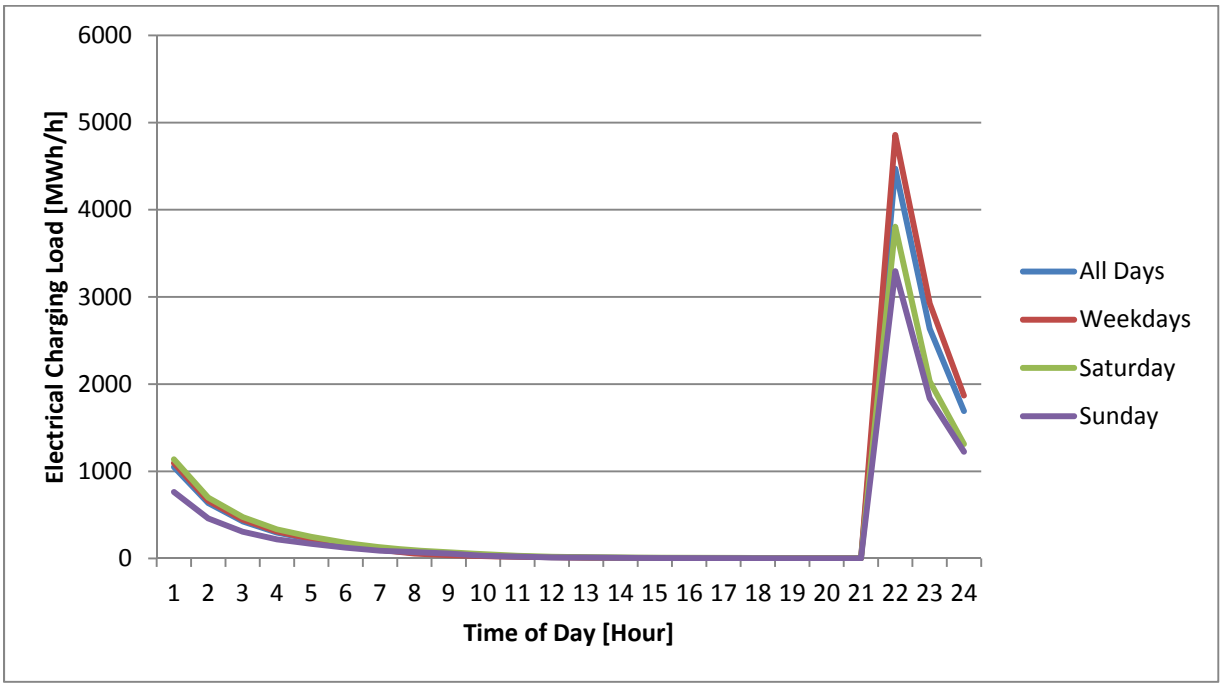

Figure 3-8 Electrical Load of 3.68kW Timed Charging in Denmark

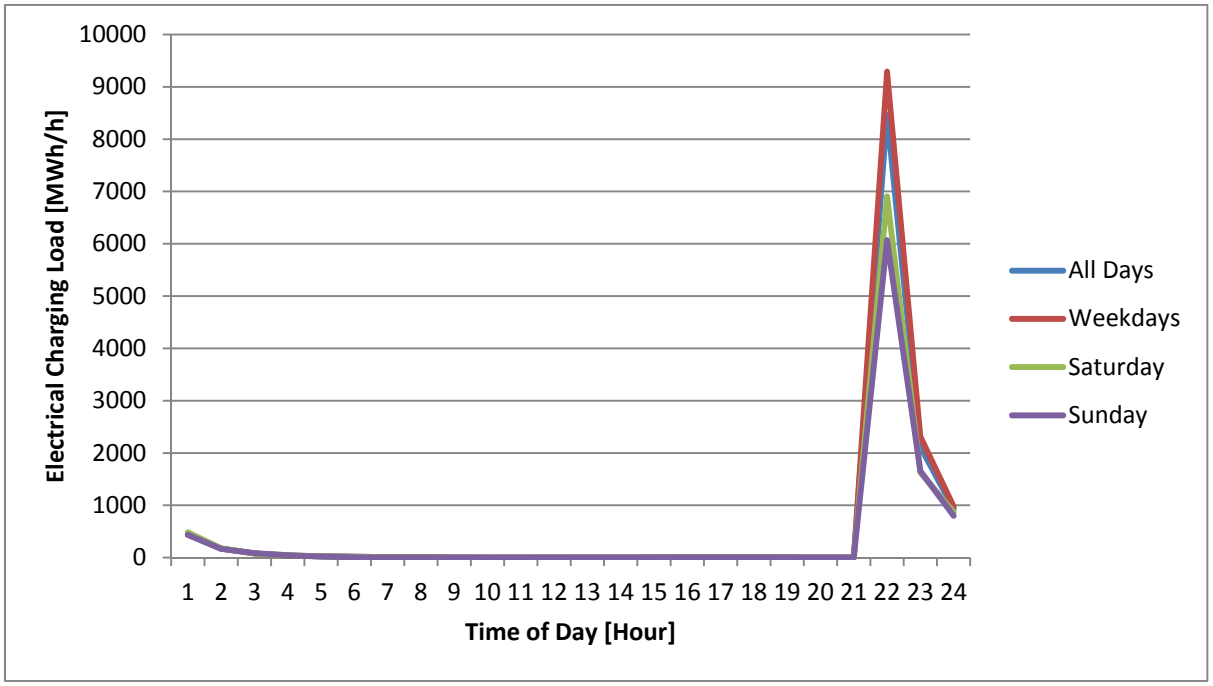

Figure 3-9 Electrical Load of 11.04kW Timed Charging in Denmark

The highest electrical charging load shows at 9-10 pm when most of the charging starts. The charging load declines steadily afterwards. Similar to the situation of dumb charging, the electrical charging load curves show to be sharper with higher charging rates. Table 3-3 shows the peak electrical charging loads of timed charging with different charging rates in Denmark. With timed charging, it is shown that most of the charging congregates in the short time slot after 9 pm, which makes a very steep spike in the charging load curve.

Table 3-3 Peak Load of Timed Charging in Denmark

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	3.35	4.86	9.29
Saturday	2.70	3.80	6.90
Sunday	2.35	3.30	6.07

3.2.3 Spot Price Based Charging Analysis

The electrical charging load curves of spot price based charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-10 to Figure 3-12 respectively.

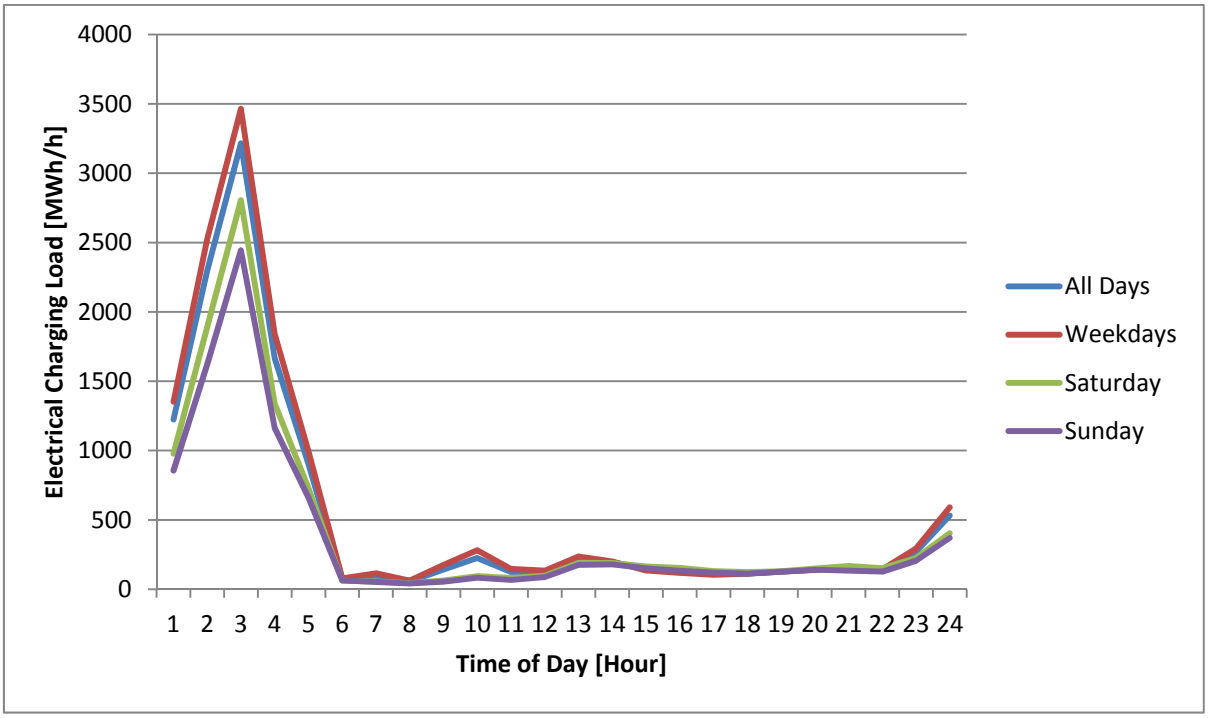

Figure 3-10 Electrical Load of 2.3kW Spot Price Based Charging All Day in Denmark

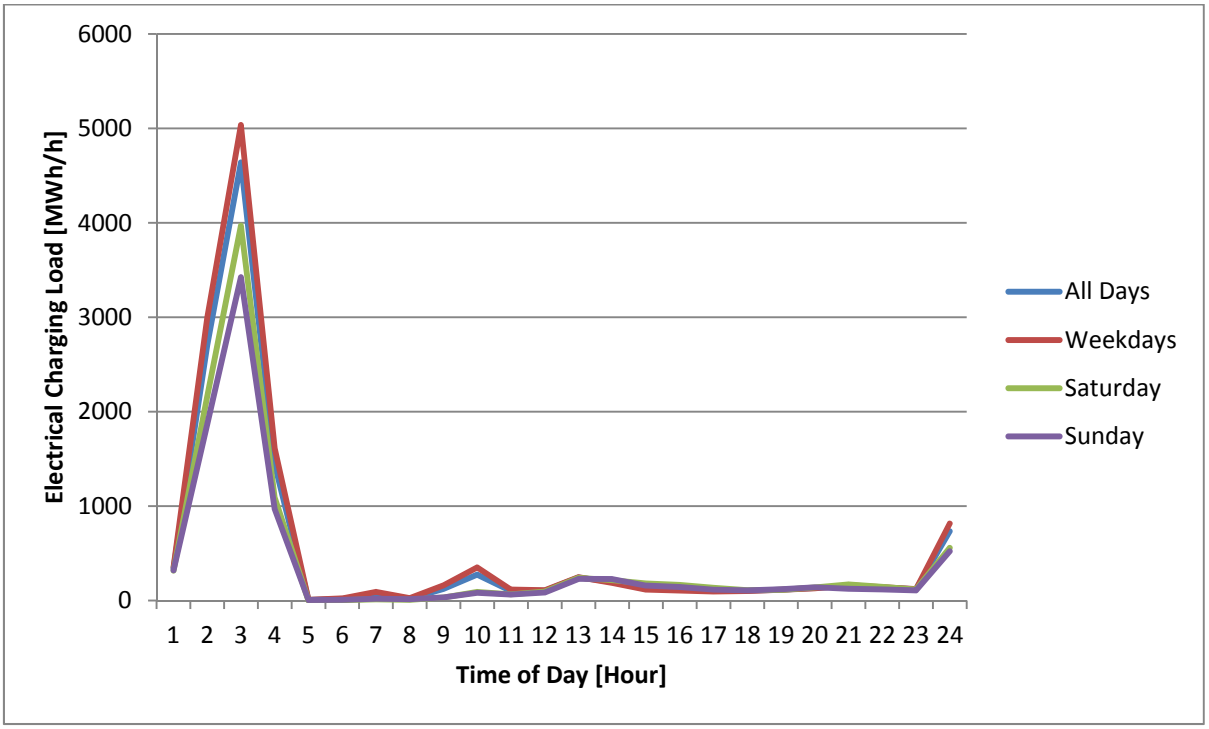

Figure 3-11 Electrical Load of 3.68kW Spot Price Based Charging All Day in Denmark

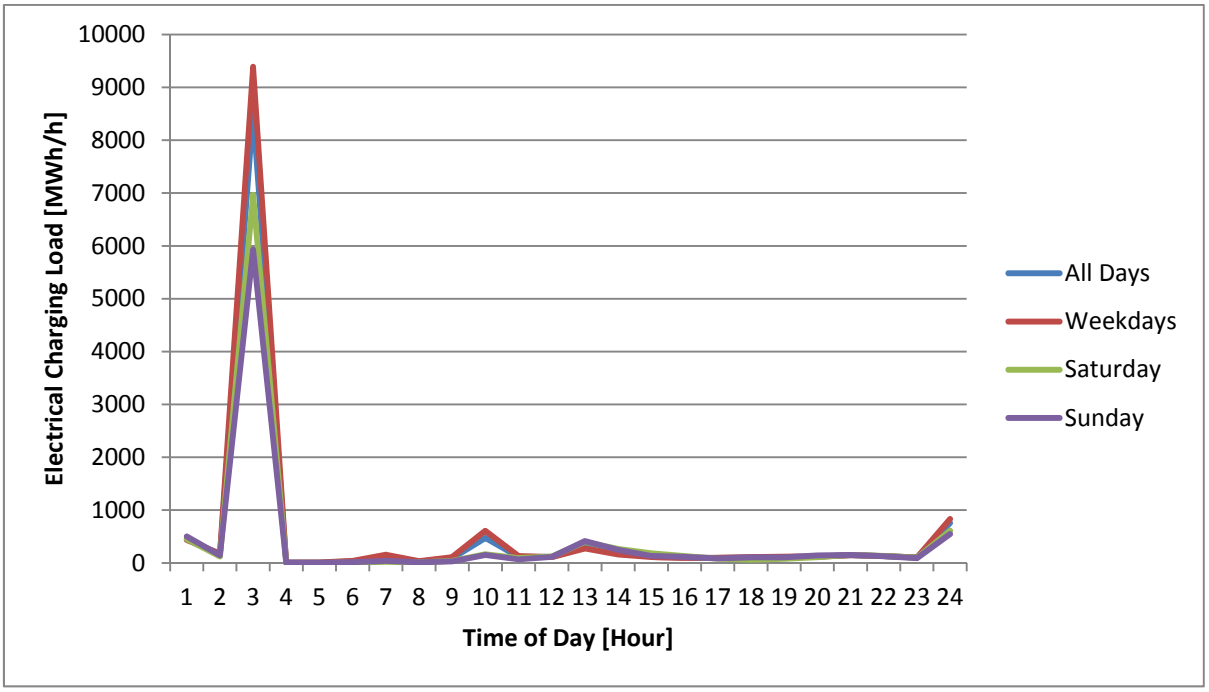

Figure 3-12 Electrical Load of 11.04kW Spot Price Based Charging All Day in Denmark

The spot price based charging is set to minimize the total charging cost while the daily energy consumption should be recovered before 6 am of the next day. Therefore, most of the charging happens at night during the hours with low spot prices and creates a spike in the charging load at that time slot.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-4 shows the peak electrical charging loads of spot price based charging all day with different charging rates in Denmark.

Table 3-4 Peak Load of Spot Price Based Charging All Day in Denmark

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	3.46	5.04	9.39
Saturday	2.81	3.97	6.96
Sunday	2.44	3.42	5.93

The electrical charging load curves of spot price based charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-13 to Figure 3-15 respectively. It is shown that there is no marked difference between the load curves of spot price based charging at home and those of spot price based charging all day.

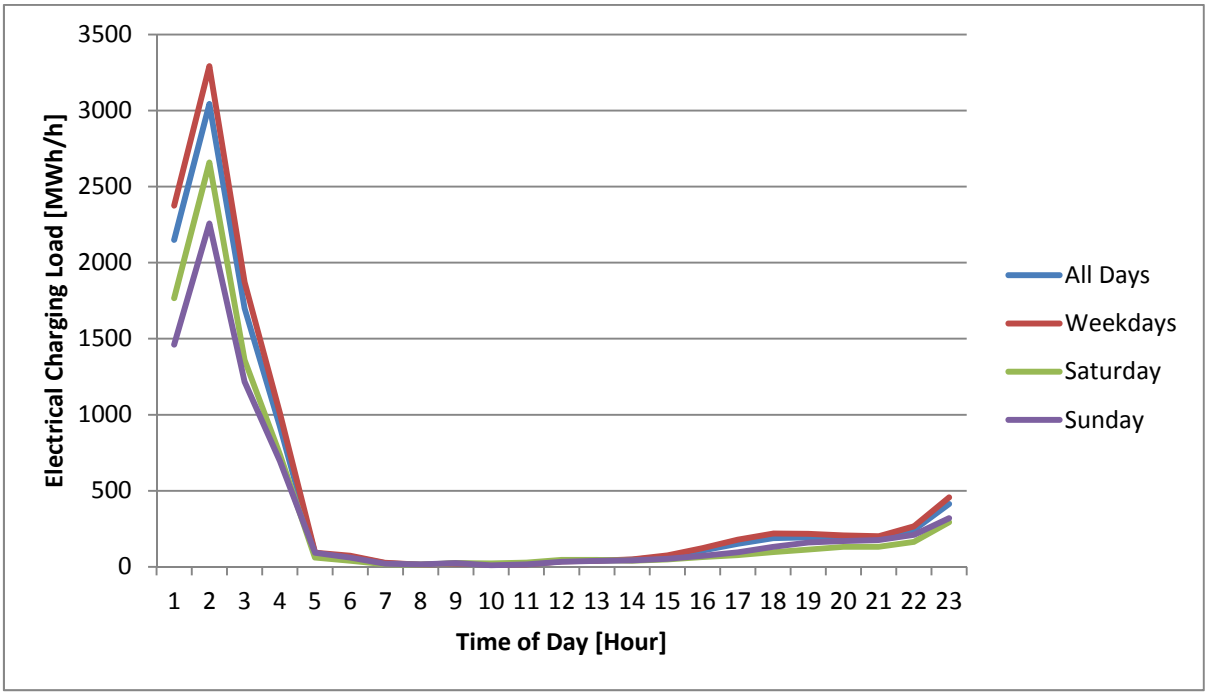

Figure 3-13 Electrical Load of 2.3kW Spot Price Based Charging at Home in Denmark

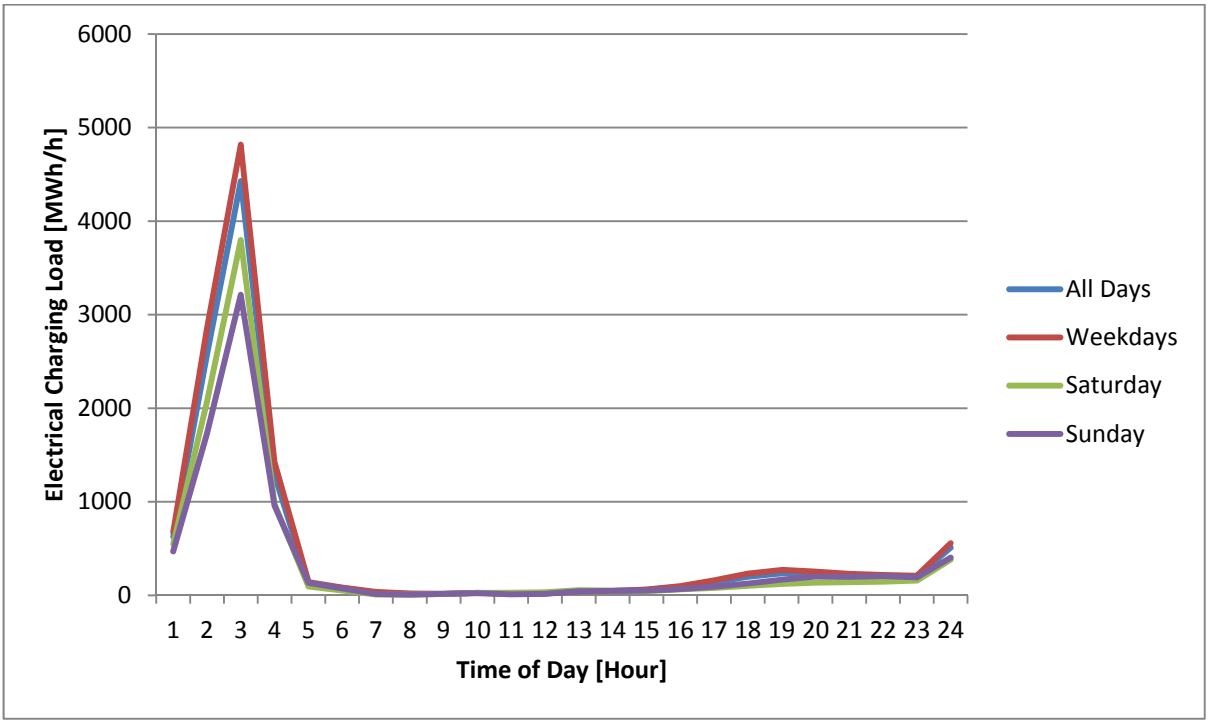

Figure 3-14 Electrical Load of 3.68kW Spot Price Based Charging at Home in Denmark

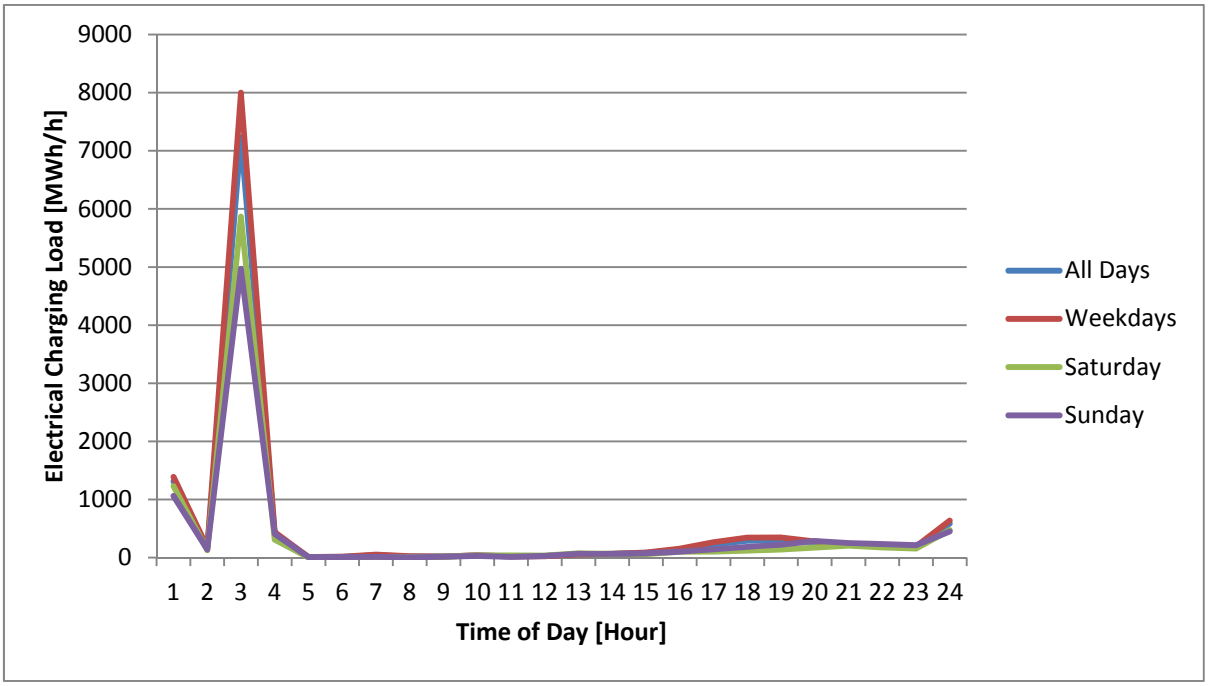

Figure 3-15 Electrical Load of 11.04kW Spot Price Based Charging at Home in Denmark

Table 3-5 shows the peak electrical charging loads of spot price based charging at home with different charging rates in Denmark. The figures are very close to the case of spot price based charging all day. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-5 Peak Load of Spot Price Based Charging at Home in Denmark

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	3.29	4.82	8.00
Saturday	2.66	3.80	5.87
Sunday	2.26	3.21	4.97

3.2.4 Impact of EV Charging on the Electric Load

Figure 3-16 shows the EV charging load curves of weekdays with different charging patterns based on the original electric load in Denmark. The charging rate of all the charging in the figure is 2.3kW (1 phase - 10A). For both dumb charging all day and dumb charging at home, the peak charging load overlaps the peak hours of the original electric load in the evening during weekdays, which has worsened the case for the electric power system. However, the worst case happens in the timed charging scenario. Although the charging begins after 9 pm when the original electric load starts to decrease, the spike of the EV charging load is so steep that it results in a similar spike in the total electric load and the highest peak load of all the cases. The spot price based charging, to some extent, moves the majority of the charging demand to the low demand period of the electric power grid at night. Nevertheless, most of the charging congregates in the hours of low electric spot prices and generates the high electrical load in the corresponding time period as a result.

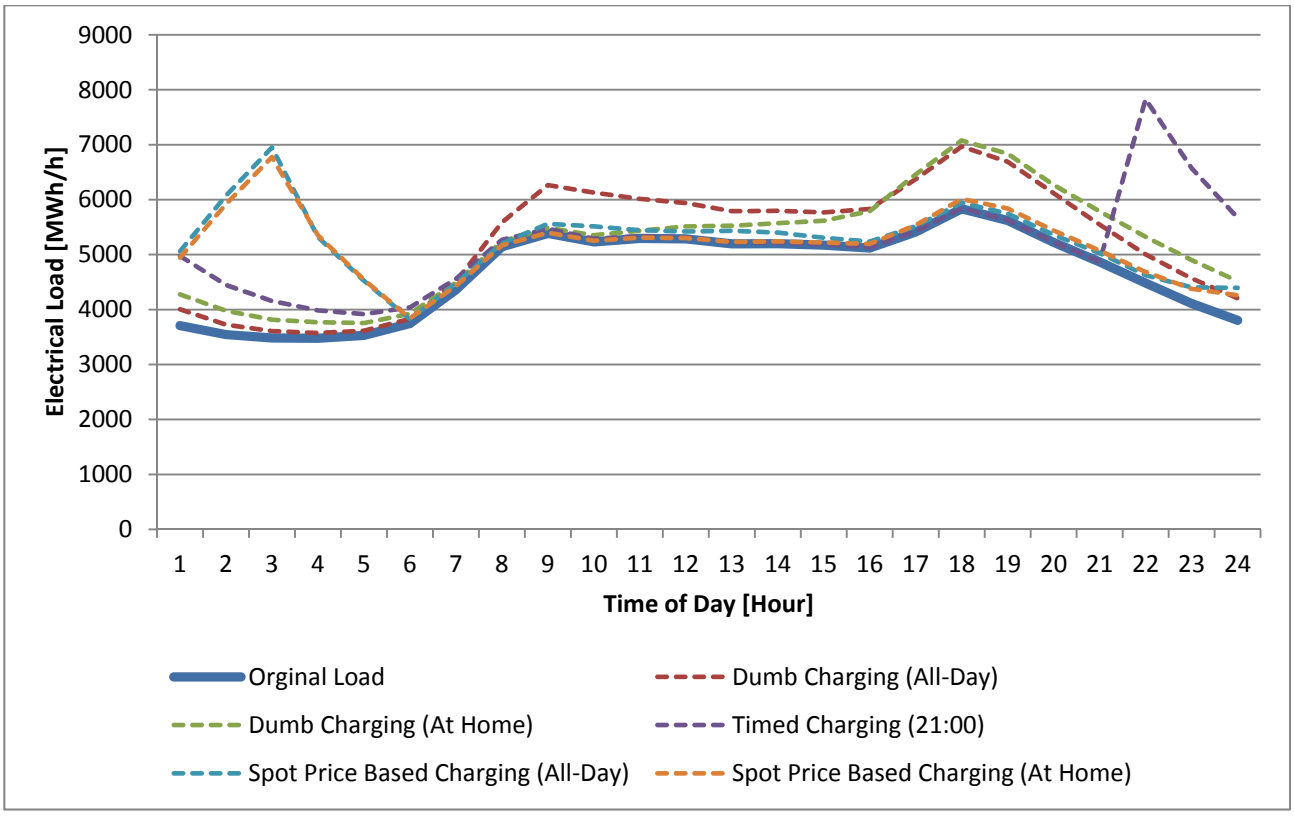

Figure 3-16 EV Charging Load of Weekdays with the Original Electric Load in Denmark

3.3 Charging Analysis with High EV Penetration in Sweden

3.3.1 Dumb Charging Analysis

The electrical charging load curves of dumb charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Sweden are shown in Figure 3-17 to Figure 3-19 respectively.

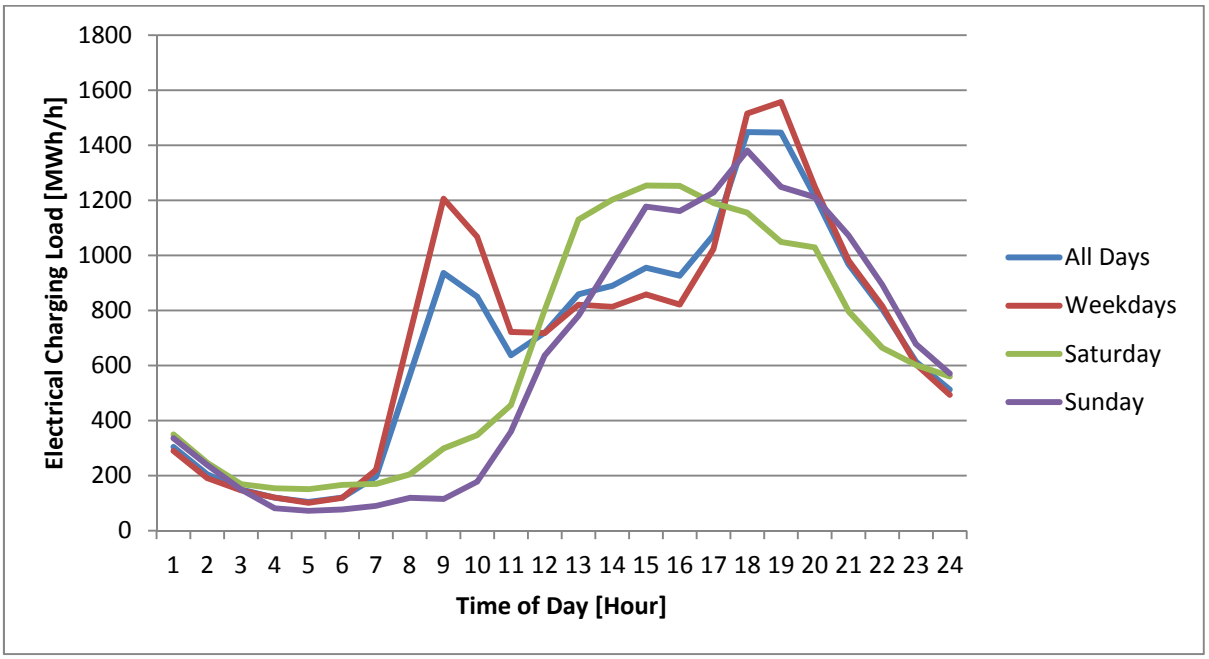

Figure 3-17 Electrical Load of 2.3kW Dumb Charging All Day in Sweden

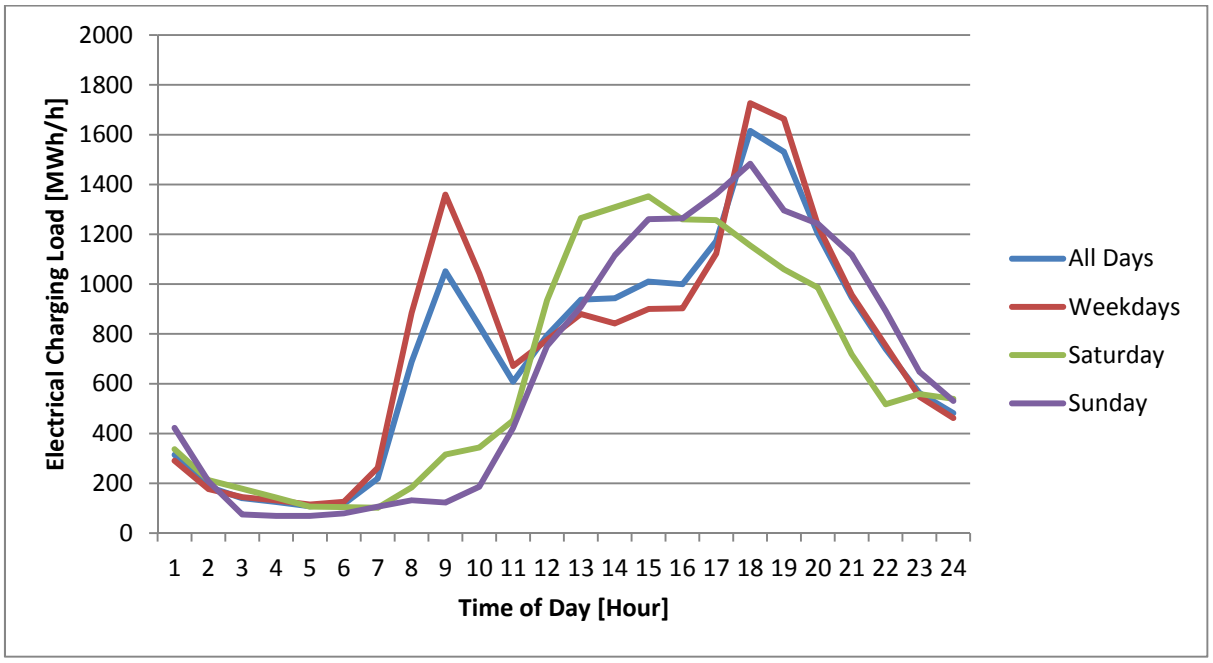

Figure 3-18 Electrical Load of 3.68kW Dumb Charging All Day in Sweden

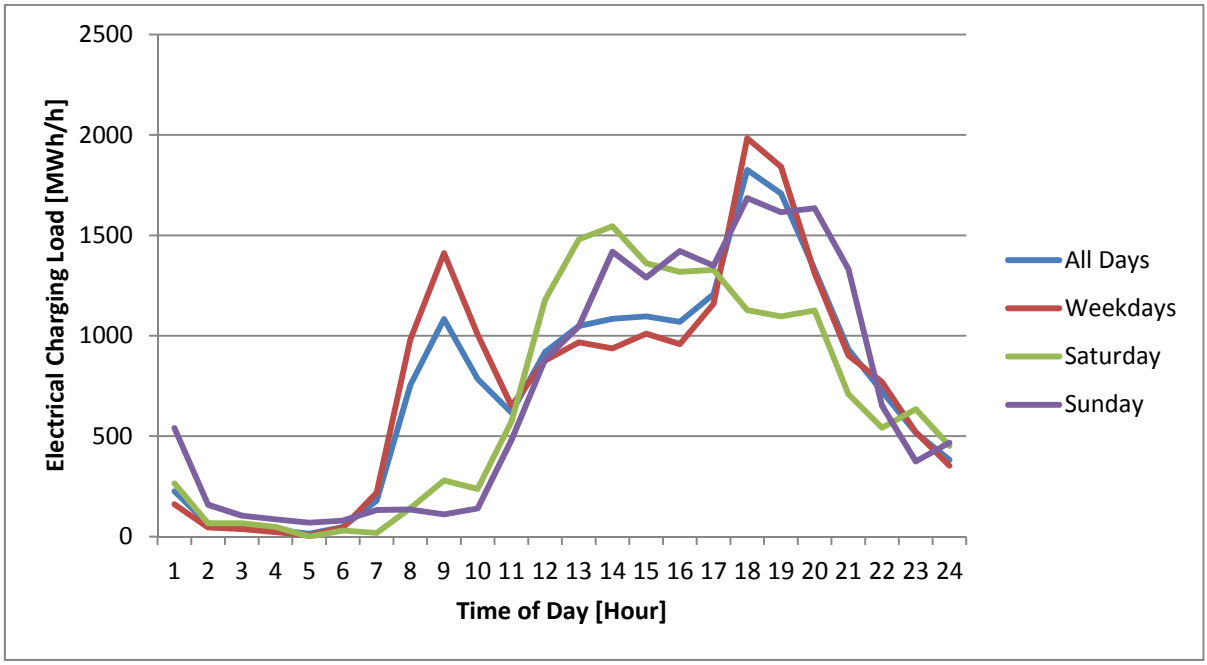

Figure 3-19 Electrical Load of 11.04kW Dumb Charging All Day in Sweden

During the weekdays, there are two spikes in the EV charging load curves of dumb charging all day in Sweden, one at 9-10 am in the morning and the other one at 6-8 pm in the evening. The highest load appears at 6-7 pm depending on the charging rates. The charging load on weekends rises late in the morning and the majority of the charging happens in the afternoon and evening. The charging load patterns are in accordance with the driving patterns of Sweden described in chapter 2.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-6 shows the peak electrical charging loads of dumb charging all day with different charging rates in Sweden.

Table 3-6 Peak Load of Dumb Charging All Day in Sweden

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.56	1.73	1.98
Saturday	1.25	1.35	1.55
Sunday	1.38	1.48	1.69

The electrical charging load curves of dumb charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-20 to Figure 3-22 respectively.

Different from the load of dumb charging all day, the load pattern of dumb charging at home has no spike in the morning on weekdays. The charging load starts to rise at 3 pm in the afternoon and comes to the peak at 6-7 pm when the most of the people are supposed to reach home from work.

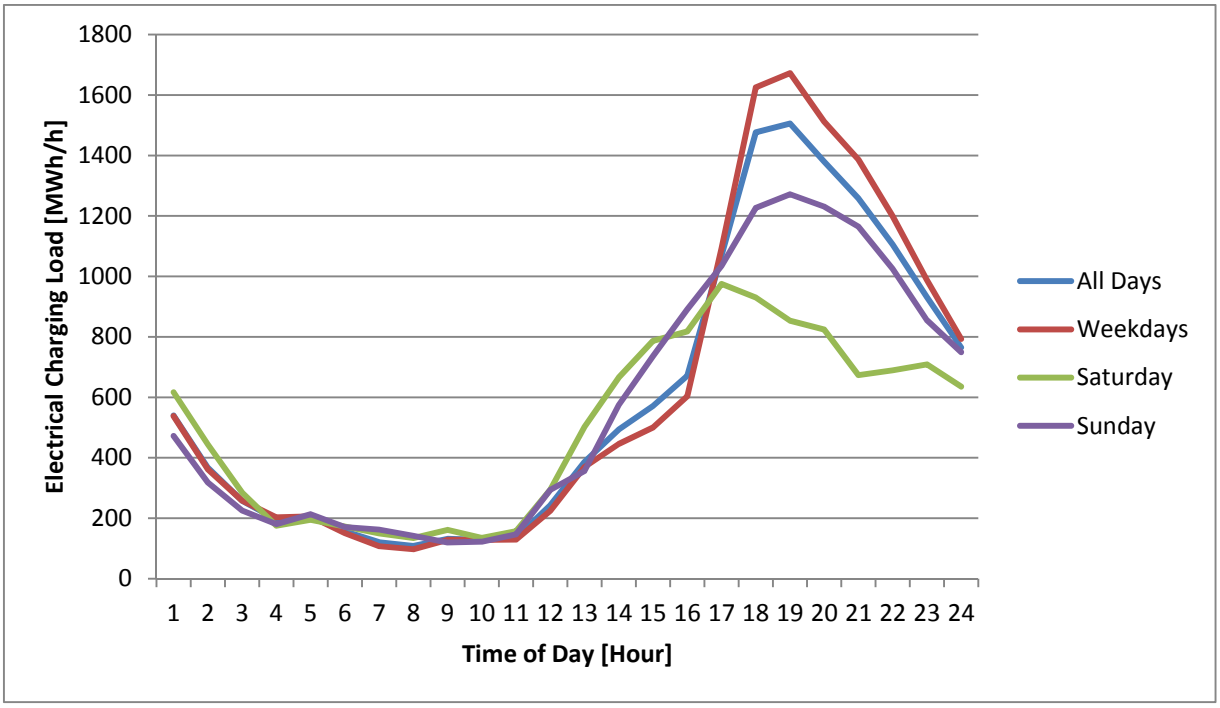

Figure 3-20 Electrical Load of 2.3kW Dumb Charging at Home in Sweden

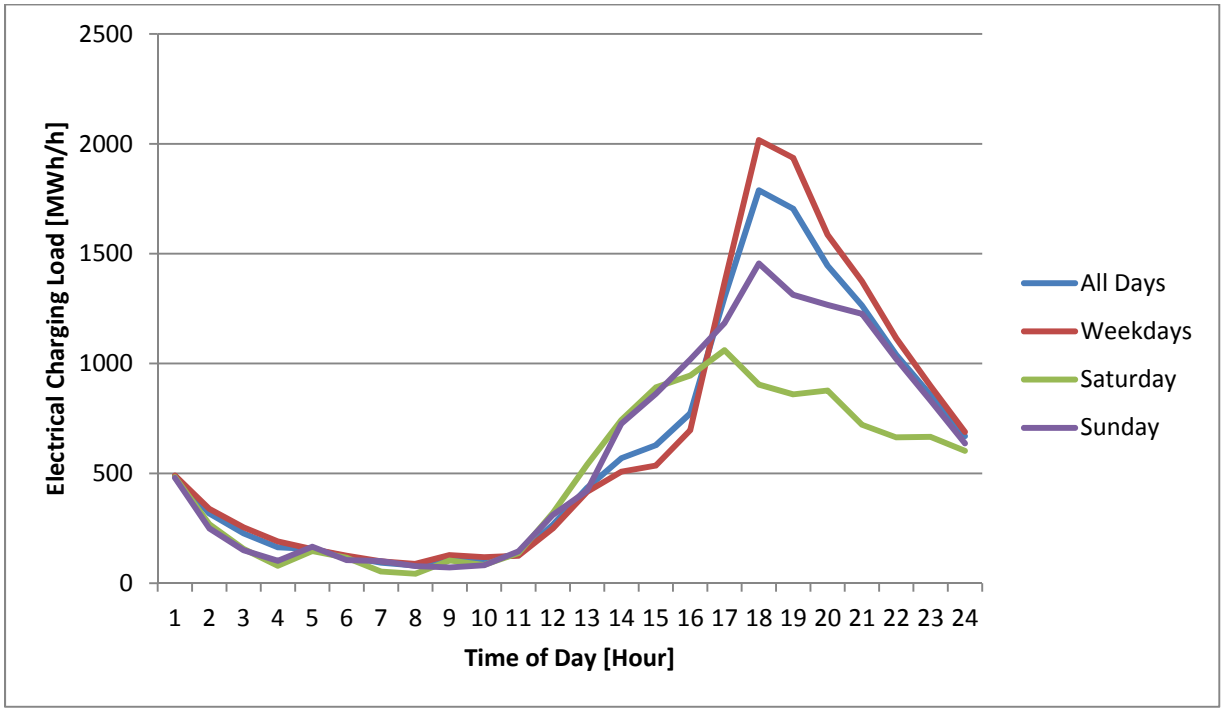

Figure 3-21 Electrical Load of 3.68kW Dumb Charging at Home in Sweden

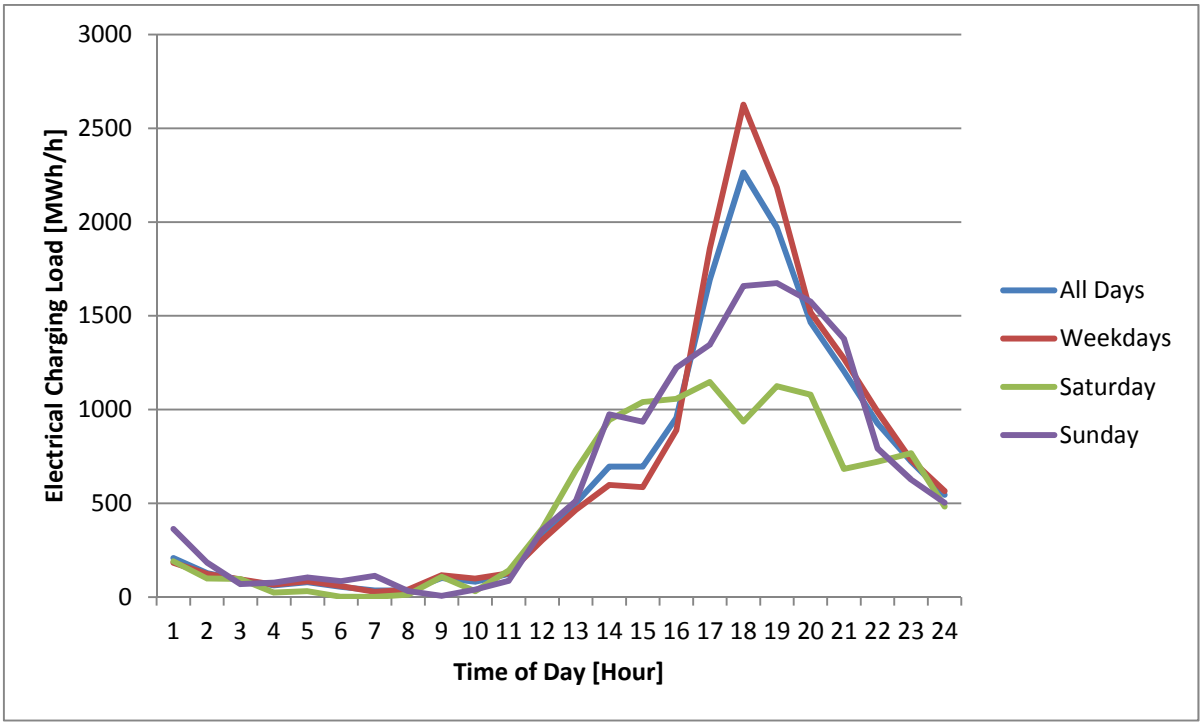

Figure 3-22 Electrical Load of 11.04kW Dumb Charging at Home in Sweden

Table 3-7 shows the peak electrical charging loads of dumb charging at home with different charging rates in Sweden. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-7 Peak Load of Dumb Charging at Home in Sweden

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.67	2.02	2.63
Saturday	0.98	1.06	1.15
Sunday	1.27	1.46	1.67

3.3.2 Timed Charging Analysis

The electrical charging load curves of timed charging that all vehicles are charged during the parking period after 9:00 pm with the charging rates of 2.3kW, 3.68kW and 11.04kW in Sweden are shown in Figure 3-23 to Figure 3-25 respectively.

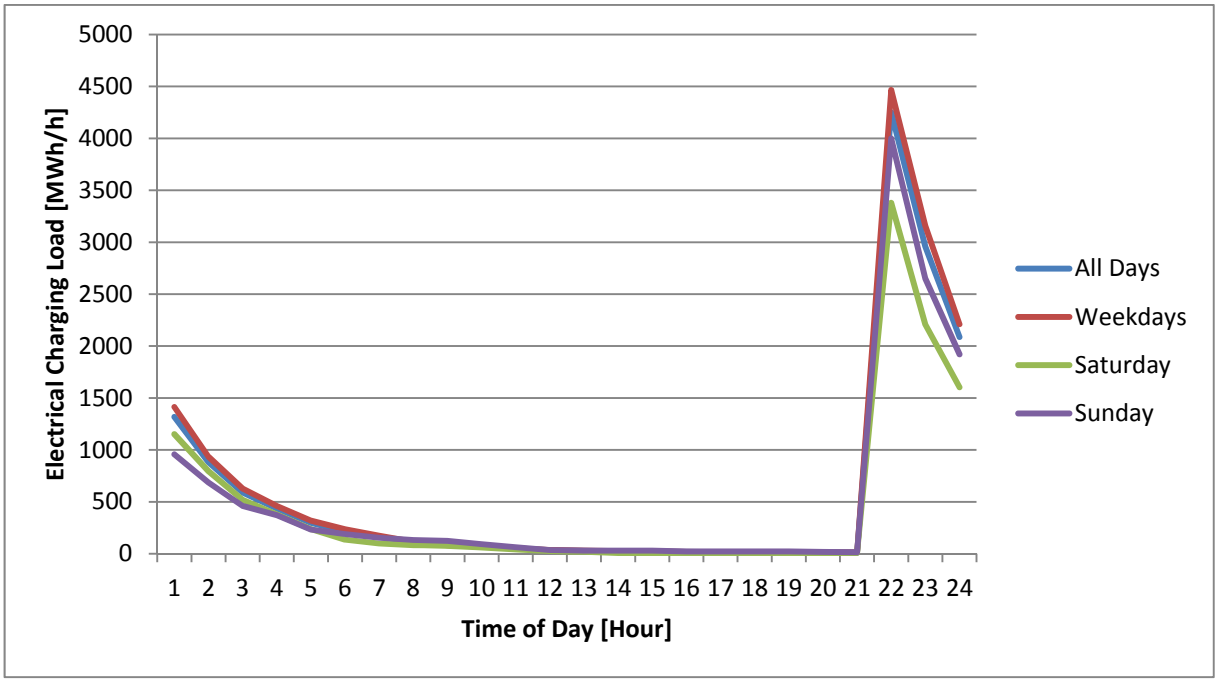

Figure 3-23 Electrical Load of 2.3kW Timed Charging in Sweden

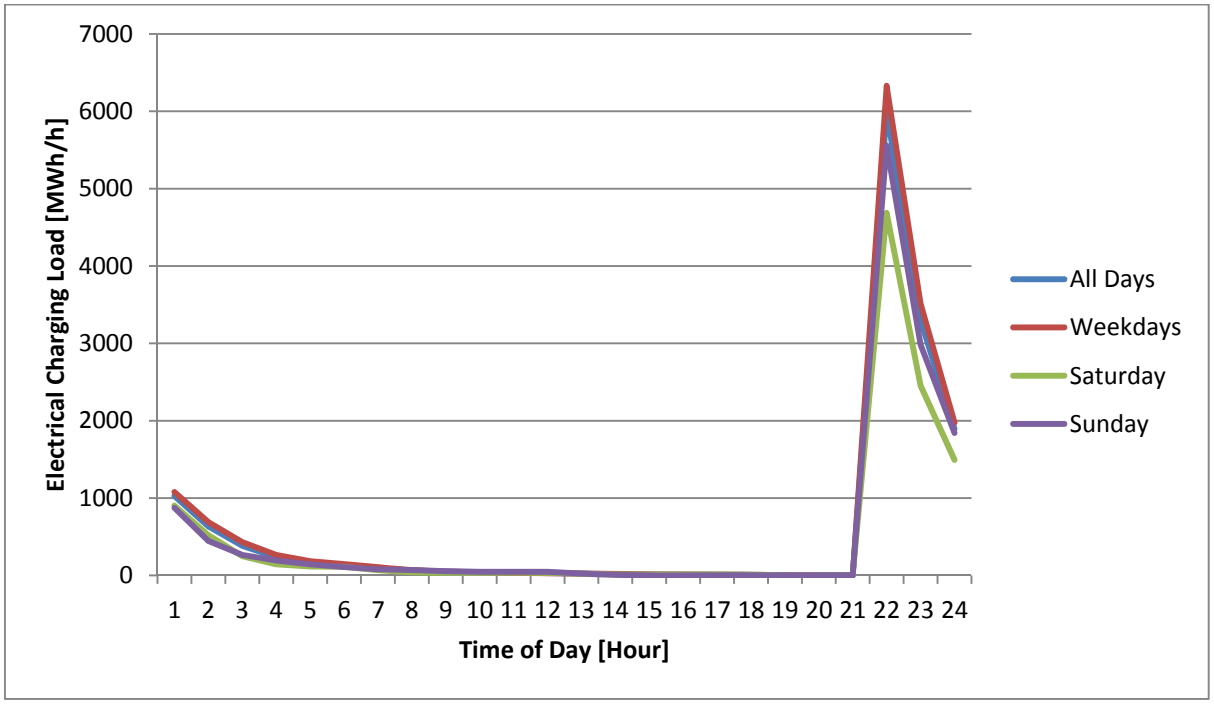

Figure 3-24 Electrical Load of 3.68kW Timed Charging in Sweden

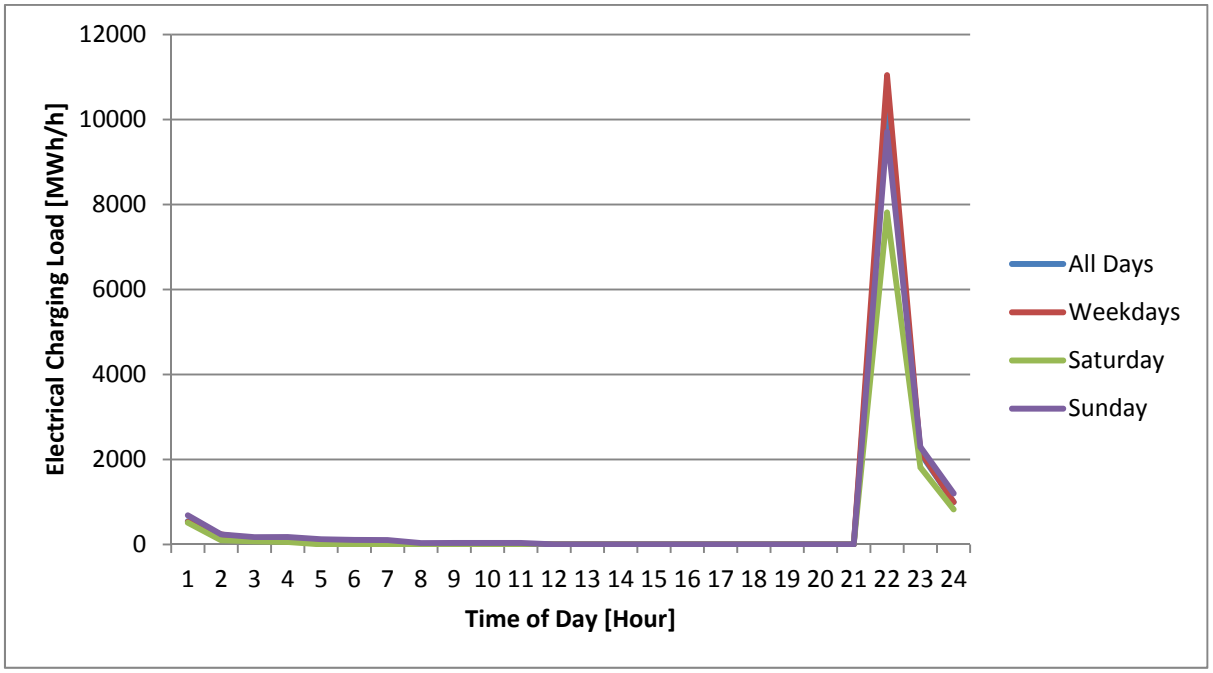

Figure 3-25 Electrical Load of 11.04kW Timed Charging in Sweden

The highest electrical charging load shows at 9-10 pm when most of the charging starts. The charging load declines steadily afterwards. Similar to the situation of dumb charging, the electrical charging load curves show to be sharper with higher charging rates. Table 3-8 shows the peak electrical charging loads of timed charging with different charging rates in Sweden. With timed charging, it is shown that most of the charging congregates in the short time slot after 9 pm, which makes a very steep spike in the charging load curve.

Table 3-8 Peak Load of Timed Charging in Sweden

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	4.46	6.33	11.04
Saturday	3.38	4.69	7.81
Sunday	4.00	5.56	9.71

3.3.3 Spot Price Based Charging Analysis

The electrical charging load curves of spot price based charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Sweden are shown in Figure 3-26 to Figure 3-28 respectively.

The spot price based charging is set to minimize the total charging cost while the daily energy consumption should be recovered before 6 am of the next day. Therefore, most of the charging happens at night during the hours with the low spot prices and leads to the high charging load at that time slot.

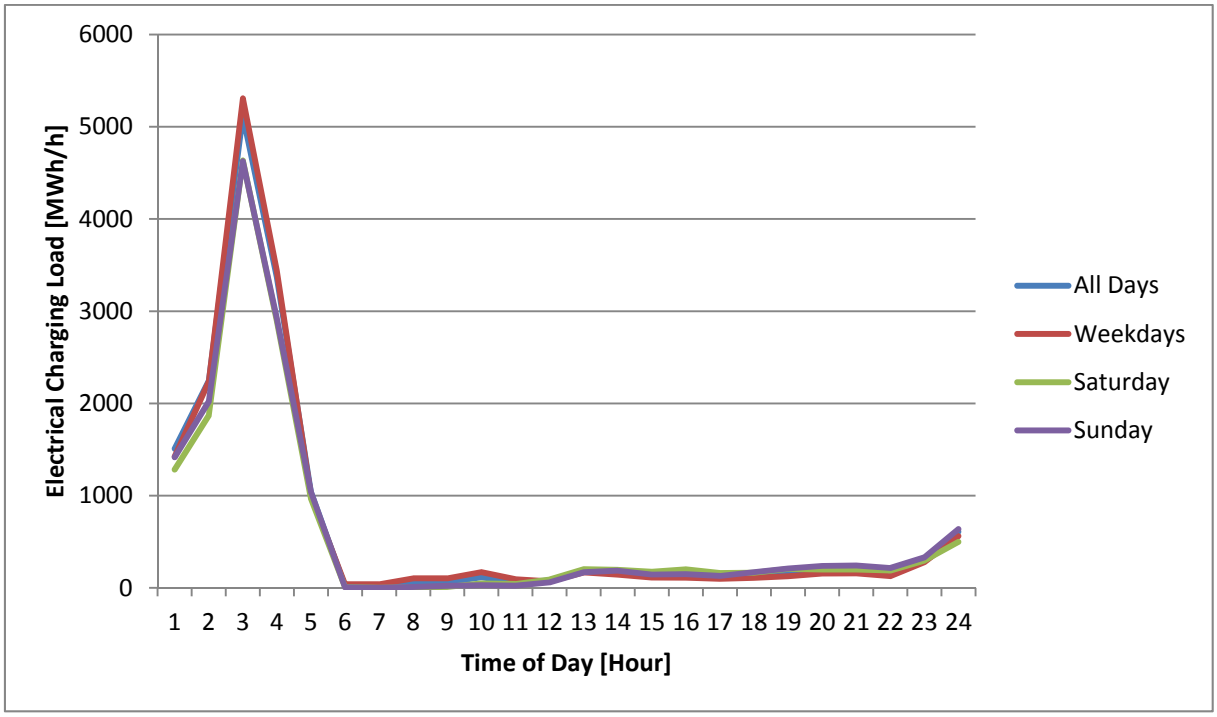

Figure 3-26 Electrical Load of 2.3kW Spot Price Based Charging All Day in Sweden

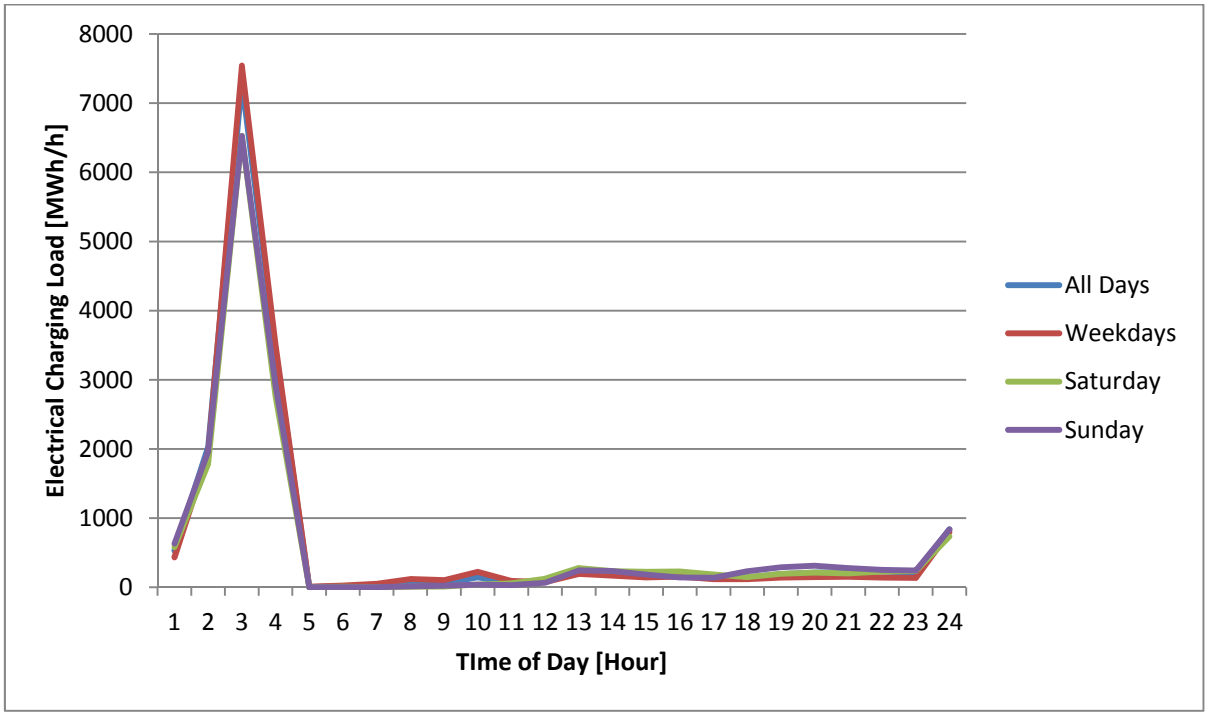

Figure 3-27 Electrical Load of 3.68kW Spot Price Based Charging All Day in Sweden

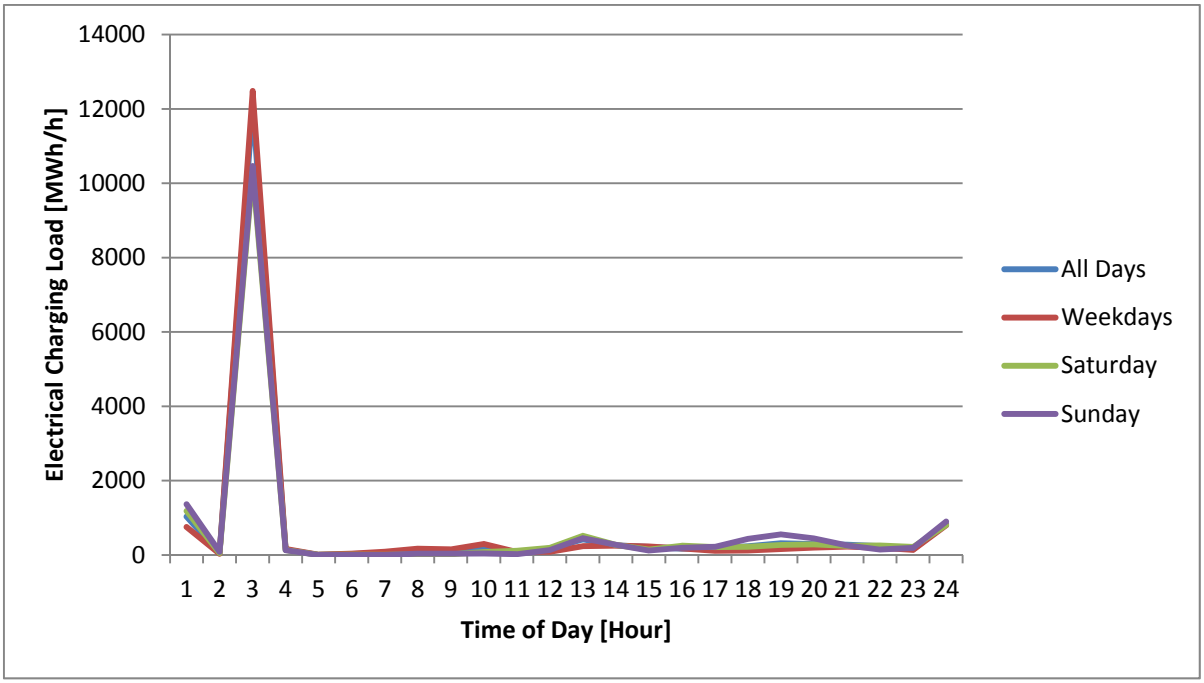

Figure 3-28 Electrical Load of 11.04kW Spot Price Based Charging All Day in Sweden

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-9 shows the peak electrical charging loads of spot price based charging all day with different charging rates in Sweden.

Table 3-9 Peak Load of Spot Price Based Charging All Day in Sweden

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	5.31	7.54	12.48
Saturday	4.63	6.53	10.29
Sunday	4.63	6.52	10.46

The electrical charging load curves of spot price based charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Sweden are shown in Figure 3-29 to Figure 3-31 respectively. It is shown that there is no marked difference between the load curves of spot price based charging at home and those of spot price based charging all day.

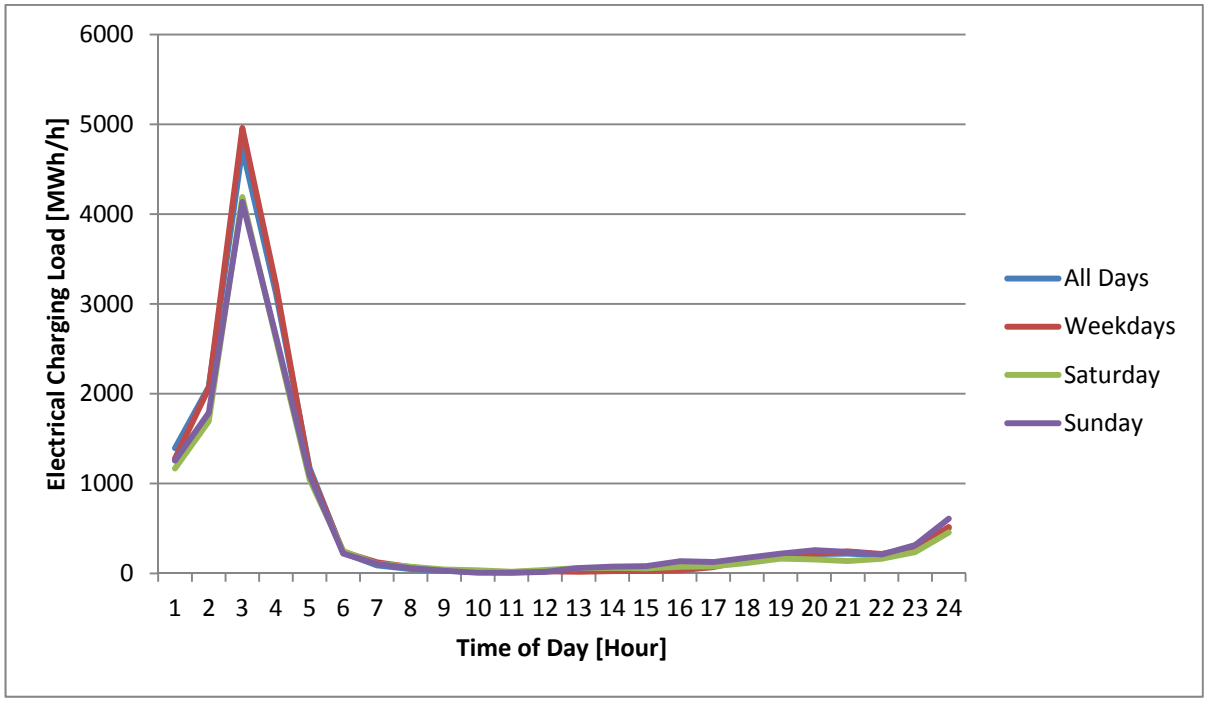

Figure 3-29 Electrical Load of 2.3kW Spot Price Based Charging at Home in Sweden

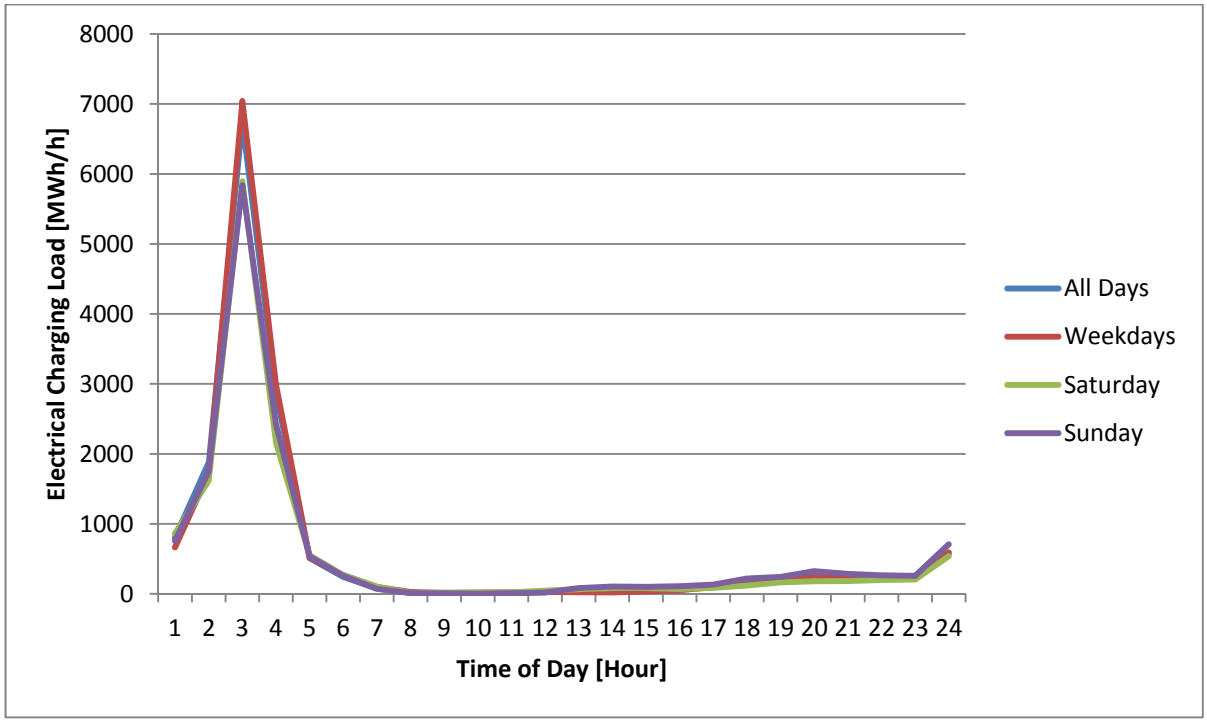

Figure 3-30 Electrical Load of 3.68kW Spot Price Based Charging at Home in Sweden

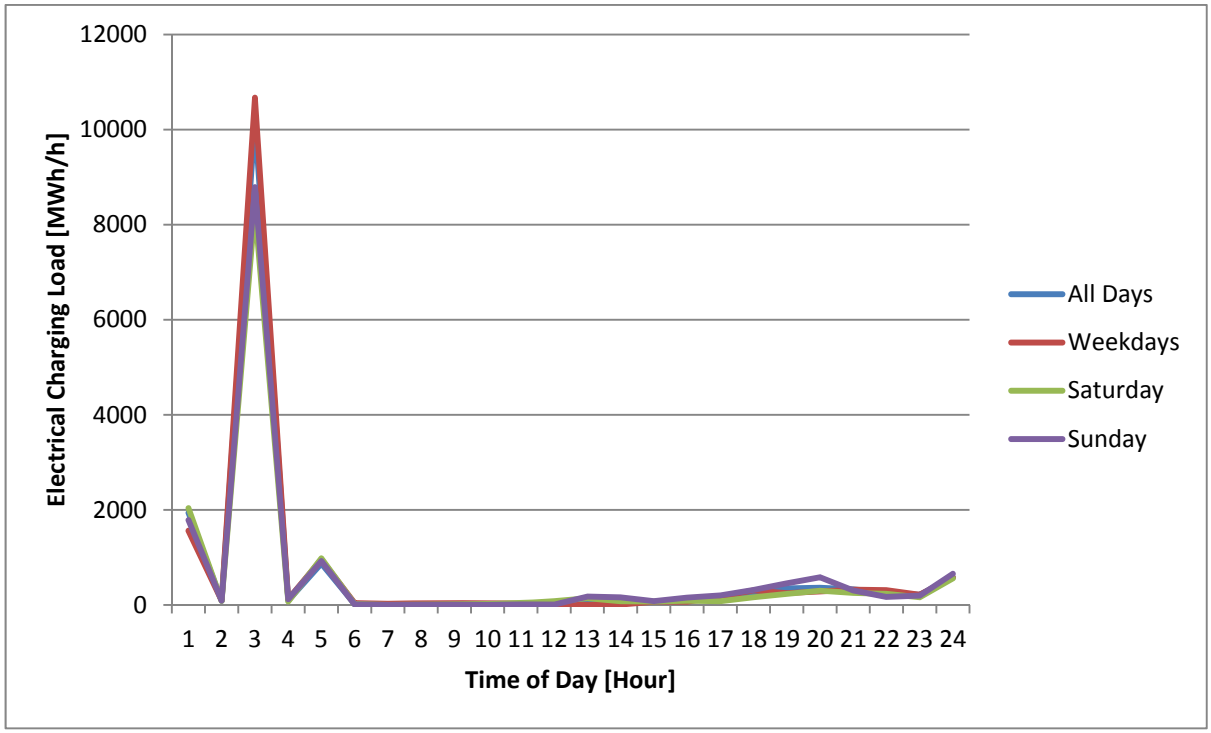

Figure 3-31 Electrical Load of 11.04kW Spot Price Based Charging at Home in Sweden

Table 3-10 shows the peak electrical charging loads of spot price based charging at home with different charging rates in Sweden. The figures are nearly the same as the case of spot price based charging all day. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-10 Peak Load of Spot Price Based Charging at Home in Sweden

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	4.96	7.04	10.67
Saturday	4.19	5.89	8.34
Sunday	4.14	5.84	8.79

3.3.4 Impact of EV Charging on the Electric Load

Figure 3-32 shows the EV charging load curves of weekdays with different charging patterns based on the original electric load in Sweden. The charging rate of all the charging in the figure is 2.3kW (1 phase - 10A). For both dumb charging all day and dumb charging at home, the peak charging load overlaps the peak hours of the original electric load in the evening during weekdays, which has worsened the case for the electric power system. For the timed charging scenario, although the charging begins after 9 pm when the original electric load tends to decrease, the spike of the EV charging load is so steep that it results in a similar spike in the total electric load. The spot price based charging, to some extent, moves the majority of the charging demand to the low demand period of the electric power grid at night. Nevertheless, most of the charging congregates in the hours with low electric spot prices and generates the high electric load in the corresponding time slot as a result.

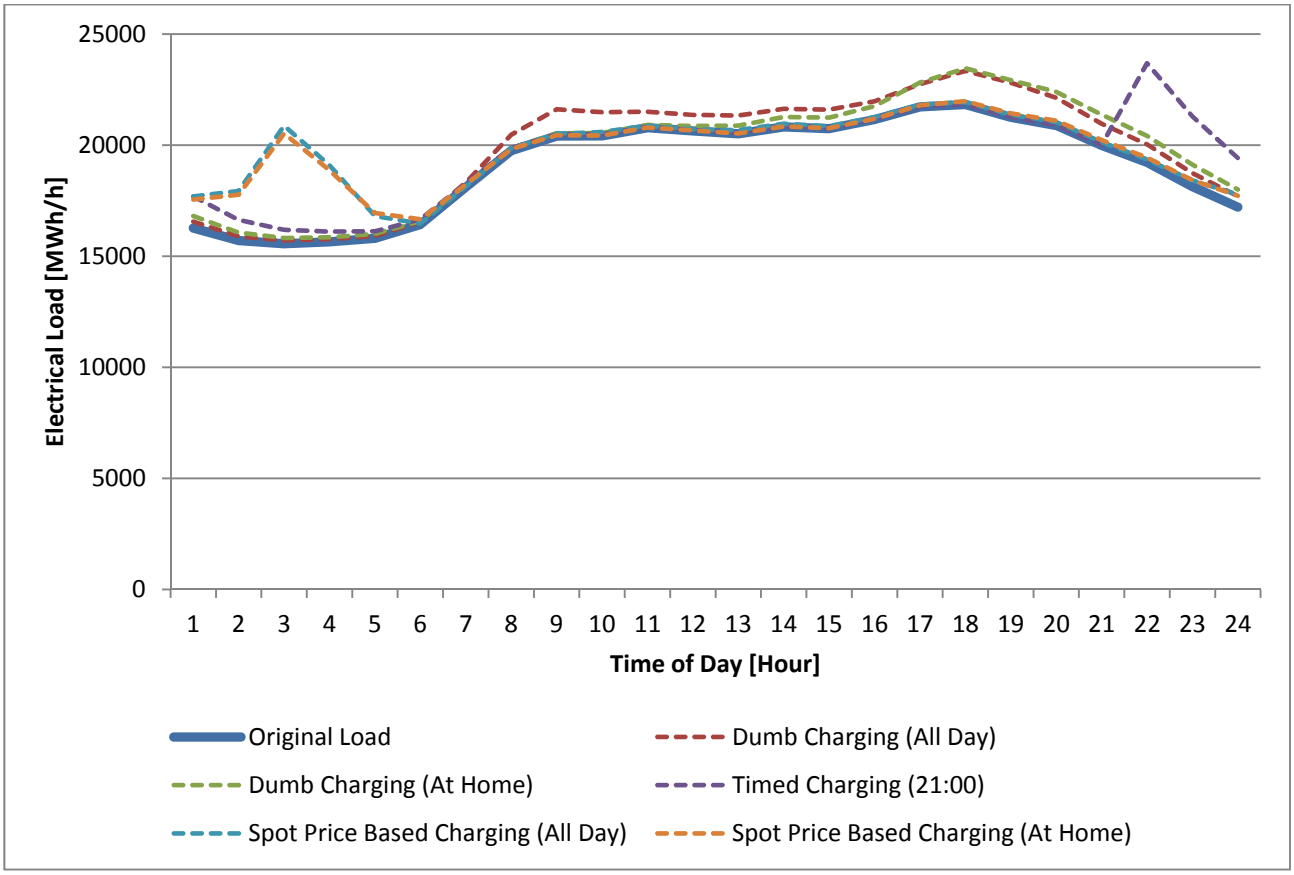

Figure 3-32 EV Charging Load of Weekdays with the Original Electric Load in Sweden

3.4 Charging Analysis with High EV Penetration in Norway

3.4.1 Dumb Charging Analysis

The electrical charging load curves of dumb charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Norway are shown in Figure 3-33 to Figure 3-35 respectively.

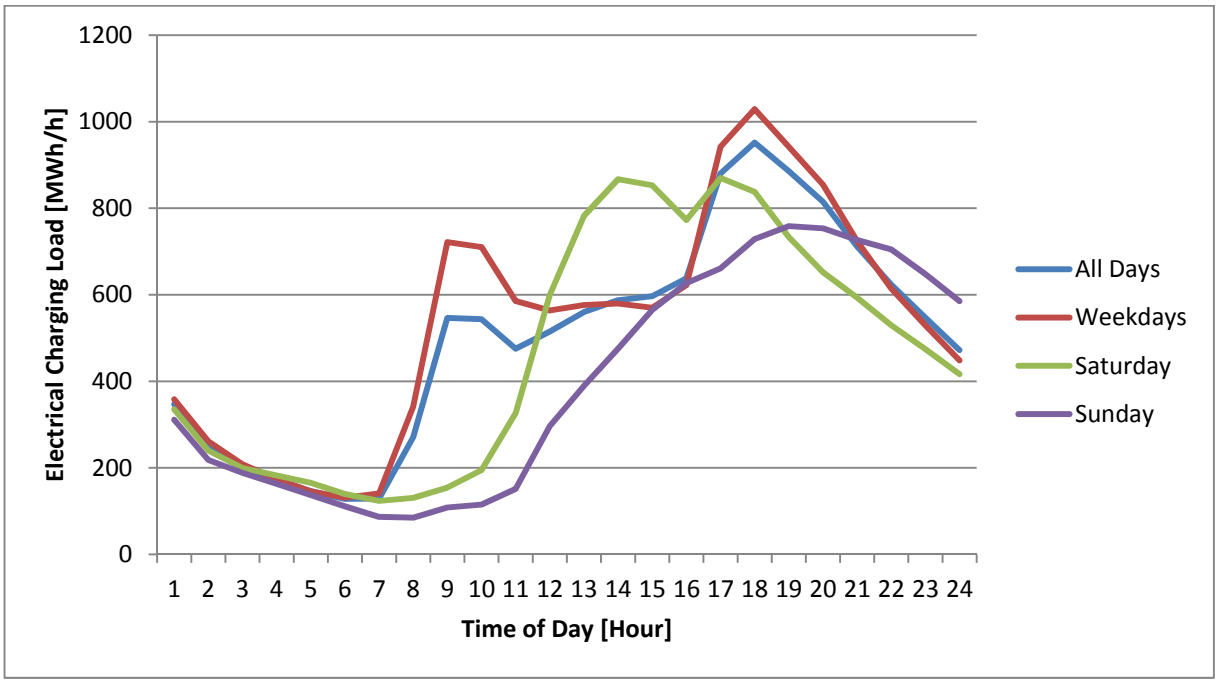

Figure 3-33 Electrical Load of 2.3kW Dumb Charging All Day in Norway

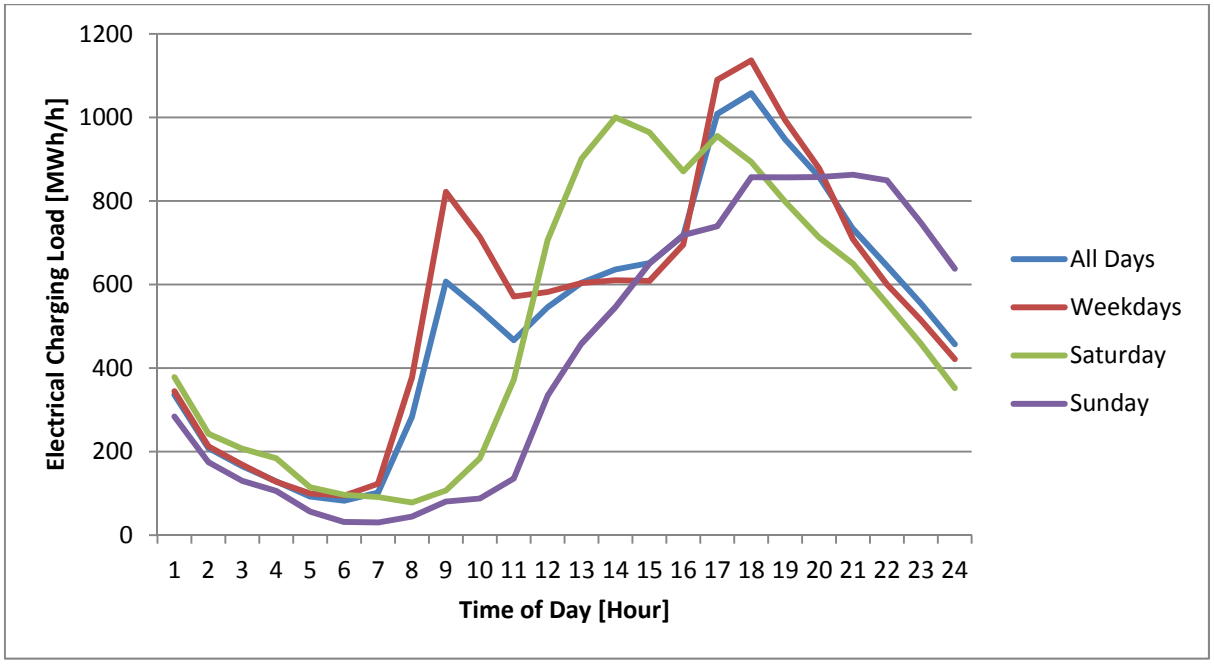

Figure 3-34 Electrical Load of 3.68kW Dumb Charging All Day in Norway

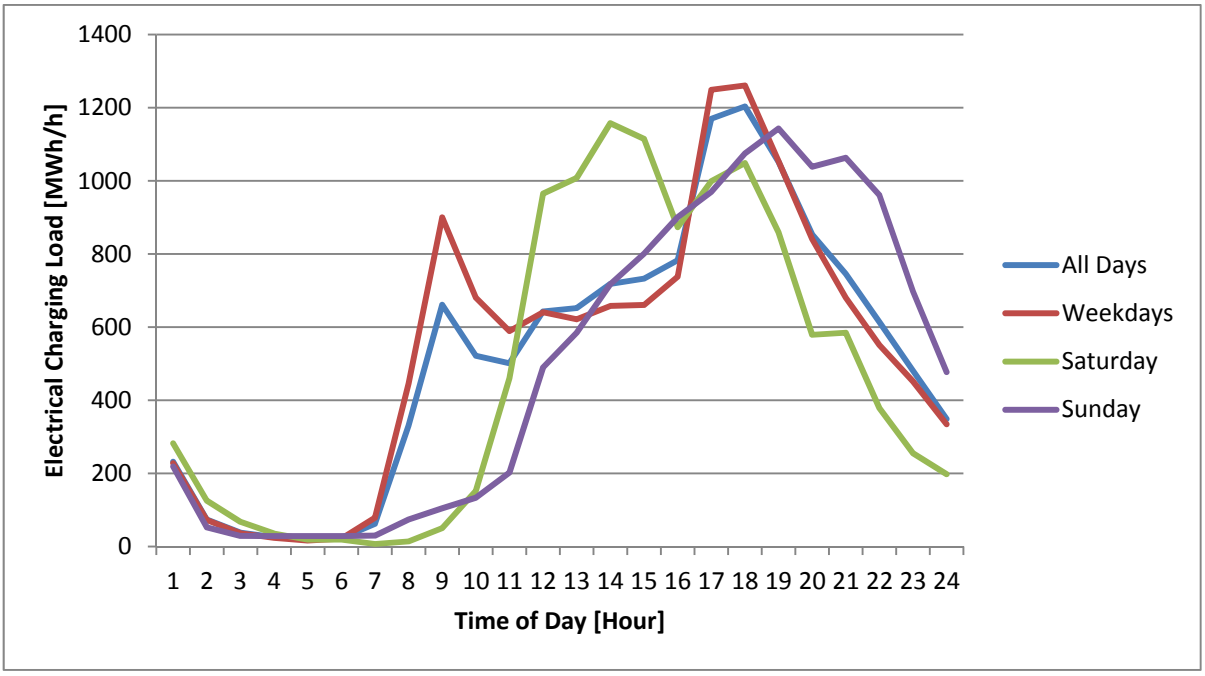

Figure 3-35 Electrical Load of 11.04kW Dumb Charging All Day in Norway

During the weekdays, there are two spikes in the EV charging load curves of dumb charging all day in Norway, one at 8-10 am in the morning and the other one at 5-7 pm in the evening. The highest load appears at around 6 pm. The charging load on weekends rises late in the morning and the majority of the charging happens in the afternoon and evening. The charging load patterns are in accordance with the driving patterns of Norway described in chapter 2.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-11 shows the peak electrical charging loads of dumb charging all day with different charging rates in Norway.

Table 3-11 Peak Load of Dumb Charging All Day in Norway

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.03	1.14	1.26
Saturday	0.87	1.00	1.16
Sunday	0.76	0.86	1.14

The electrical charging load curves of dumb charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Denmark are shown in Figure 3-36 to Figure 3-38 respectively.

Different from the load of dumb charging all day, the load pattern of dumb charging at home has no spike in the morning on weekdays. The charging load starts to rise at 3 pm in the afternoon and comes to the peak at around 4-6 pm when the most of the people are supposed to reach home from work.

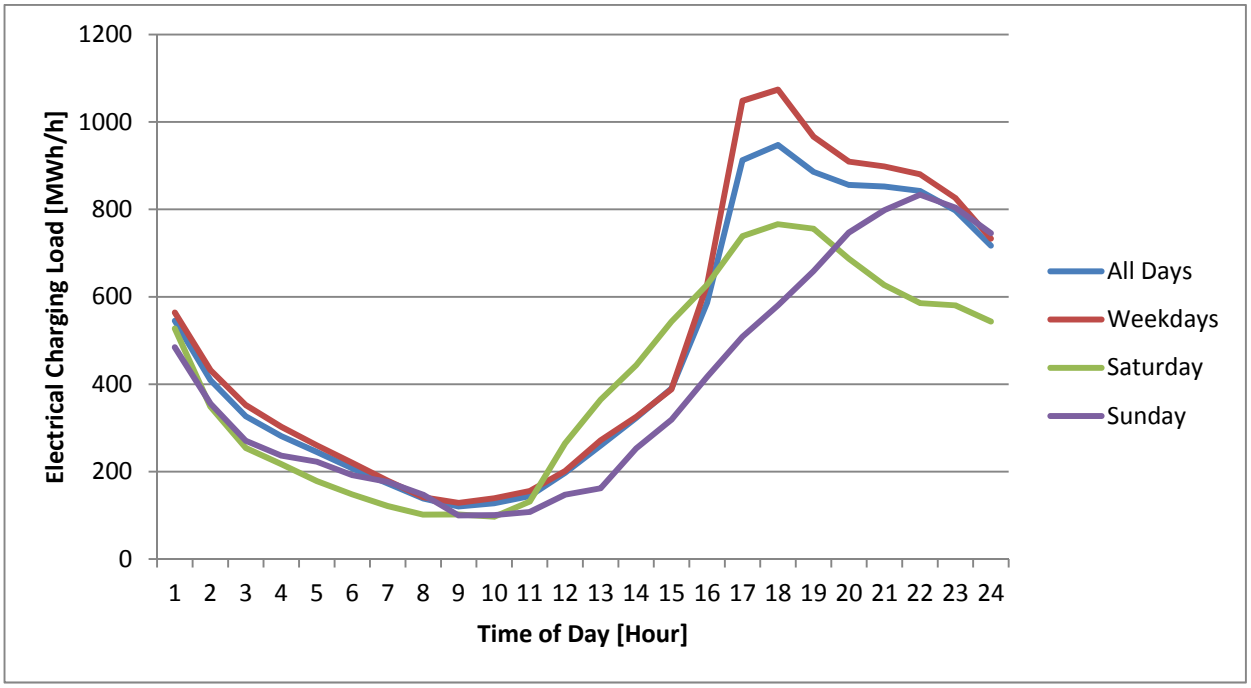

Figure 3-36 Electrical Load of 2.3kW Dumb Charging at Home in Norway

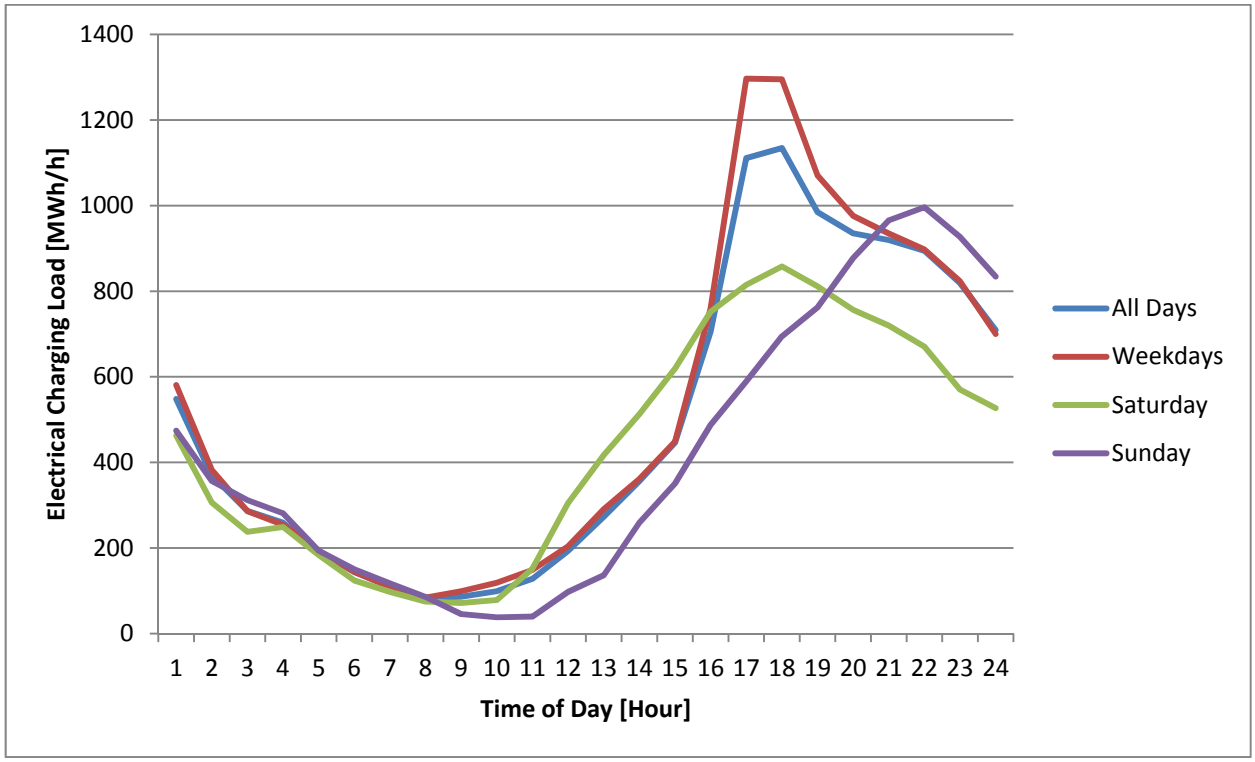

Figure 3-37 Electrical Load of 3.68kW Dumb Charging at Home in Norway

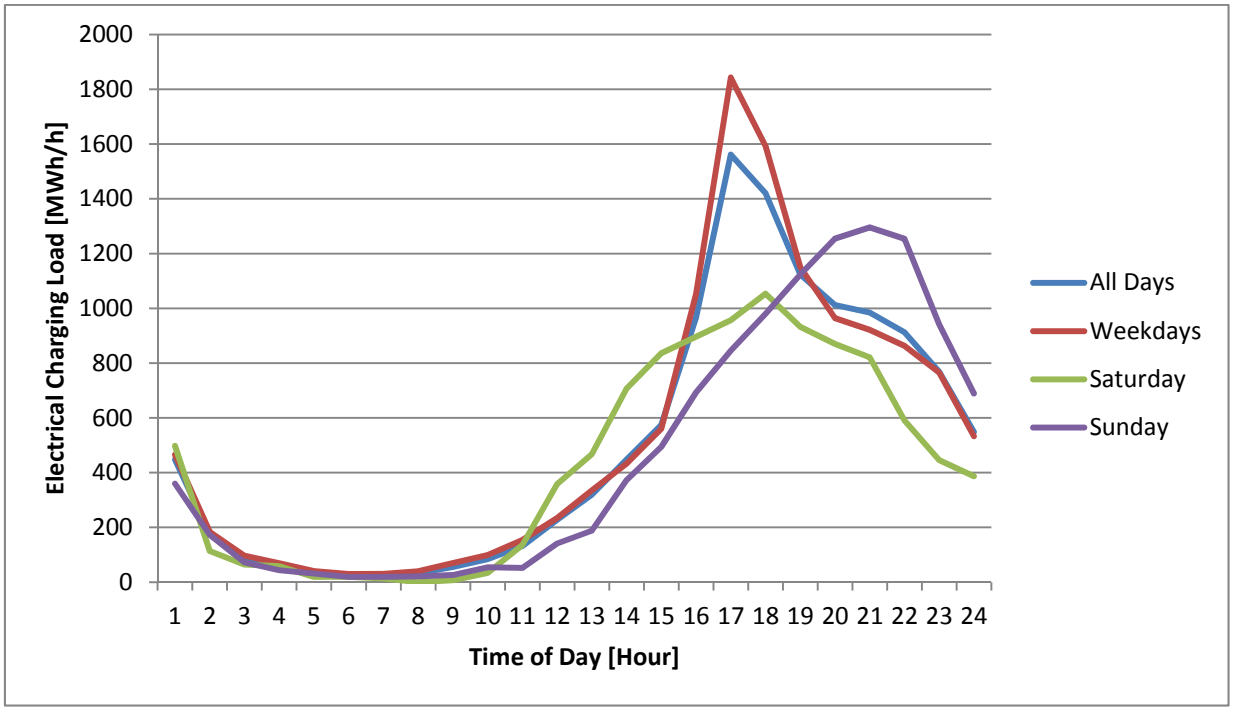

Figure 3-38 Electrical Load of 11.04kW Dumb Charging at Home in Norway

Table 3-12 shows the peak electrical charging loads of dumb charging at home with different charging rates in Norway. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-12 Peak Load of Dumb Charging at Home in Norway

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.07	1.30	1.84
Saturday	0.77	0.86	1.05
Sunday	0.83	1.00	1.30

3.4.2 Timed Charging Analysis

The electrical charging load curves of timed charging that all vehicles are charged during the parking period after 9:00 pm with the charging rates of 2.3kW, 3.68kW and 11.04kW in Norway are shown in Figure 3-39 to Figure 3-41 respectively.

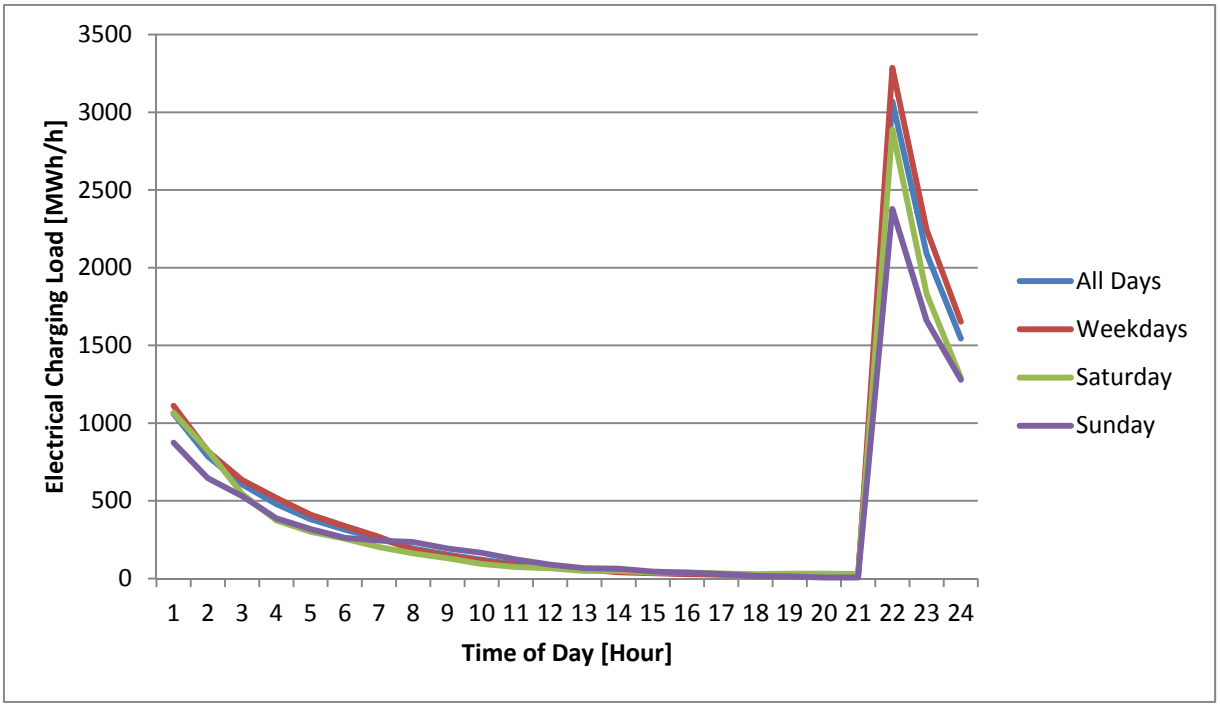

Figure 3-39 Electrical Load of 2.3kW Timed Charging in Norway

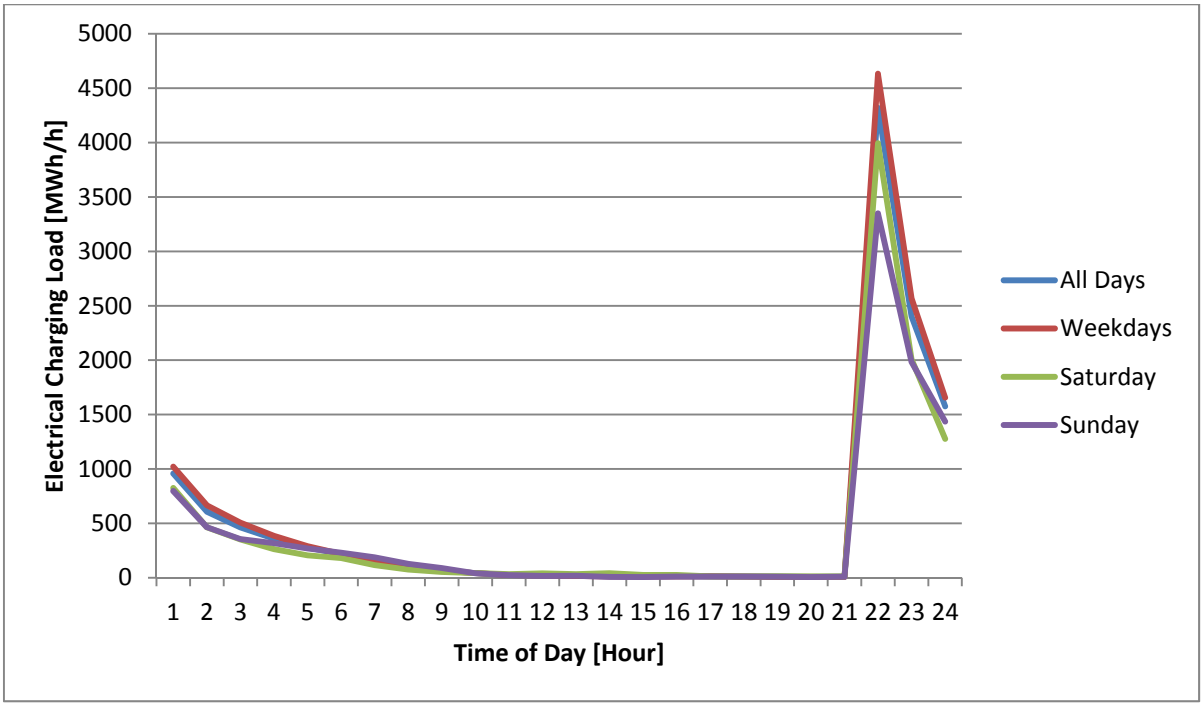

Figure 3-40 Electrical Load of 3.68kW Timed Charging in Norway

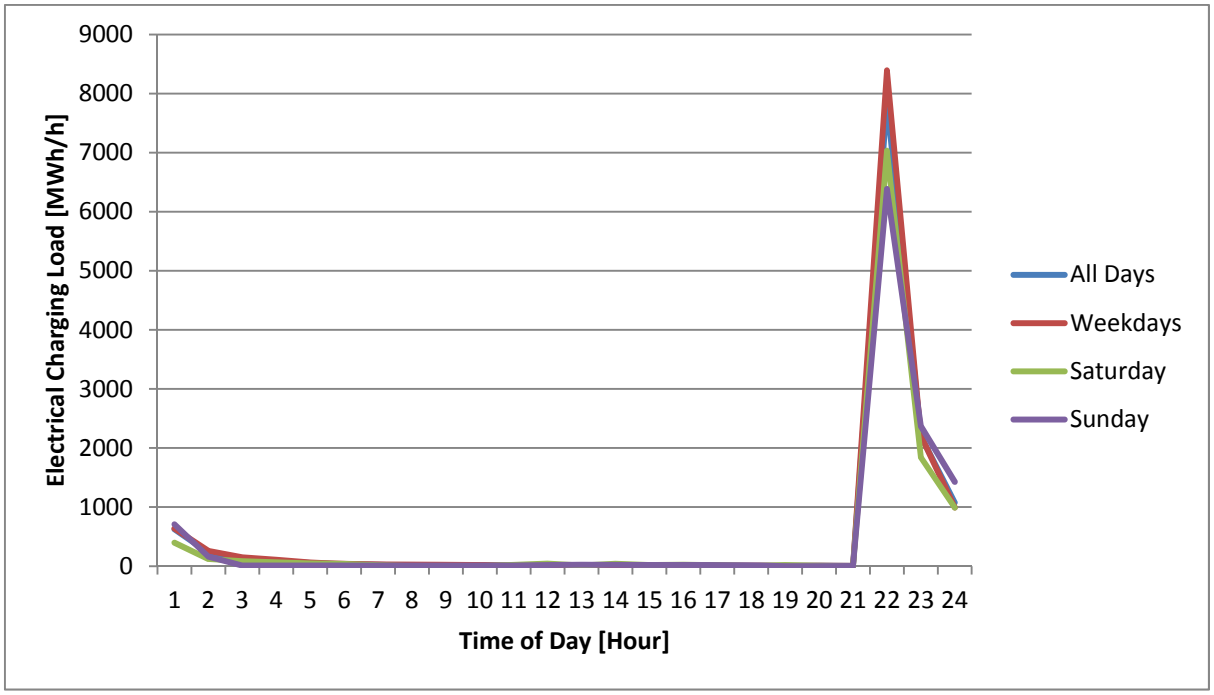

Figure 3-41 Electrical Load of 11.04kW Timed Charging in Norway

The highest electrical charging load shows at 9-10 pm when most of the charging starts. The charging load declines steadily afterwards. Similar to the situation of dumb charging, the electrical charging load curves show to be sharper with higher charging rates. Table 3-13 shows the peak electrical charging loads of timed charging with different charging rates in Norway. With timed charging, it is shown that most of the charging congregates in the short time slot after 9 pm, which makes a very steep spike in the charging load curve.

Table 3-13 Peak Load of Timed Charging in Norway

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	3.29	4.63	8.39
Saturday	2.89	3.99	7.03
Sunday	2.38	3.35	6.39

3.4.3 Spot Price Based Charging Analysis

The electrical charging load curves of spot price based charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Norway are shown in Figure 3-42 to Figure 3-44 respectively.

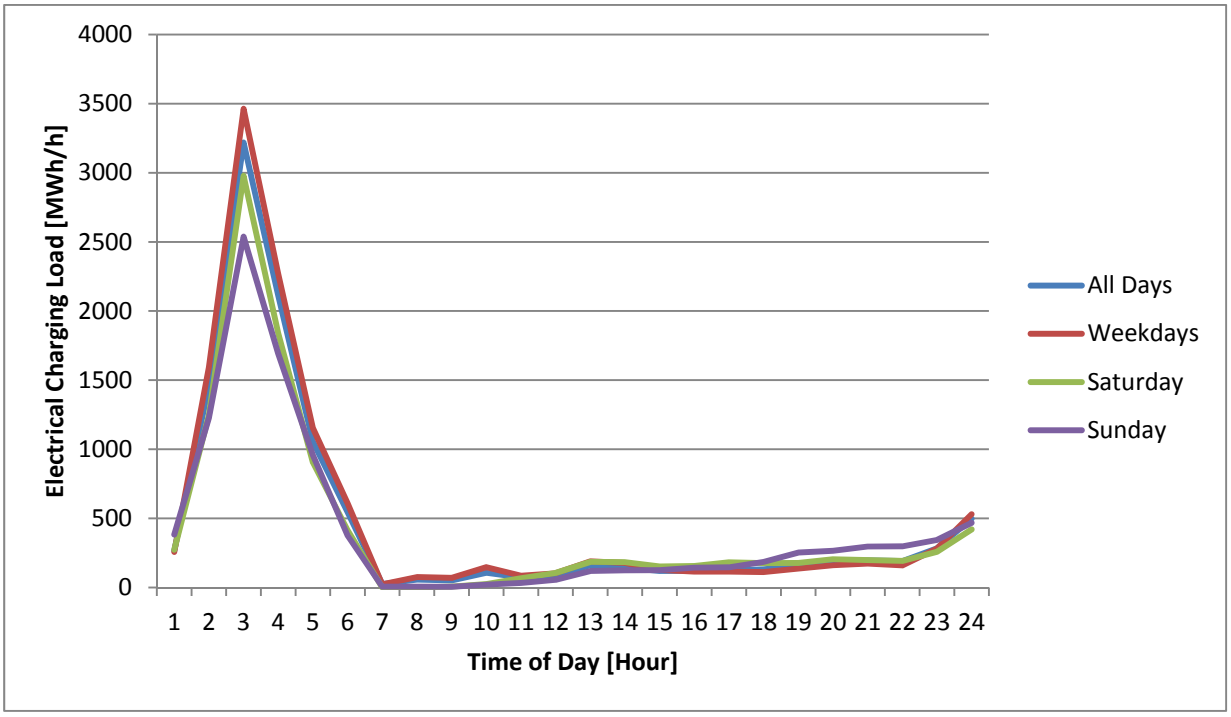

Figure 3-42 Electrical Load of 2.3kW Spot Price Based Charging All Day in Norway

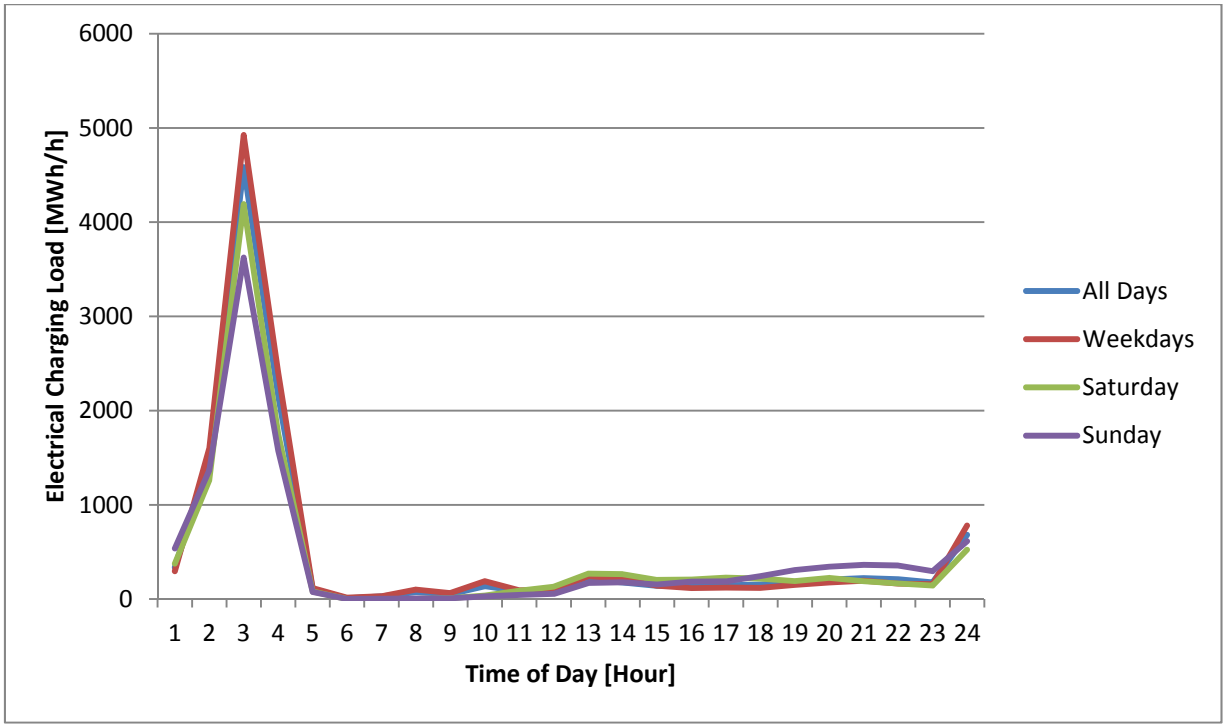

Figure 3-43 Electrical Load of 3.68kW Spot Price Based Charging All Day in Norway

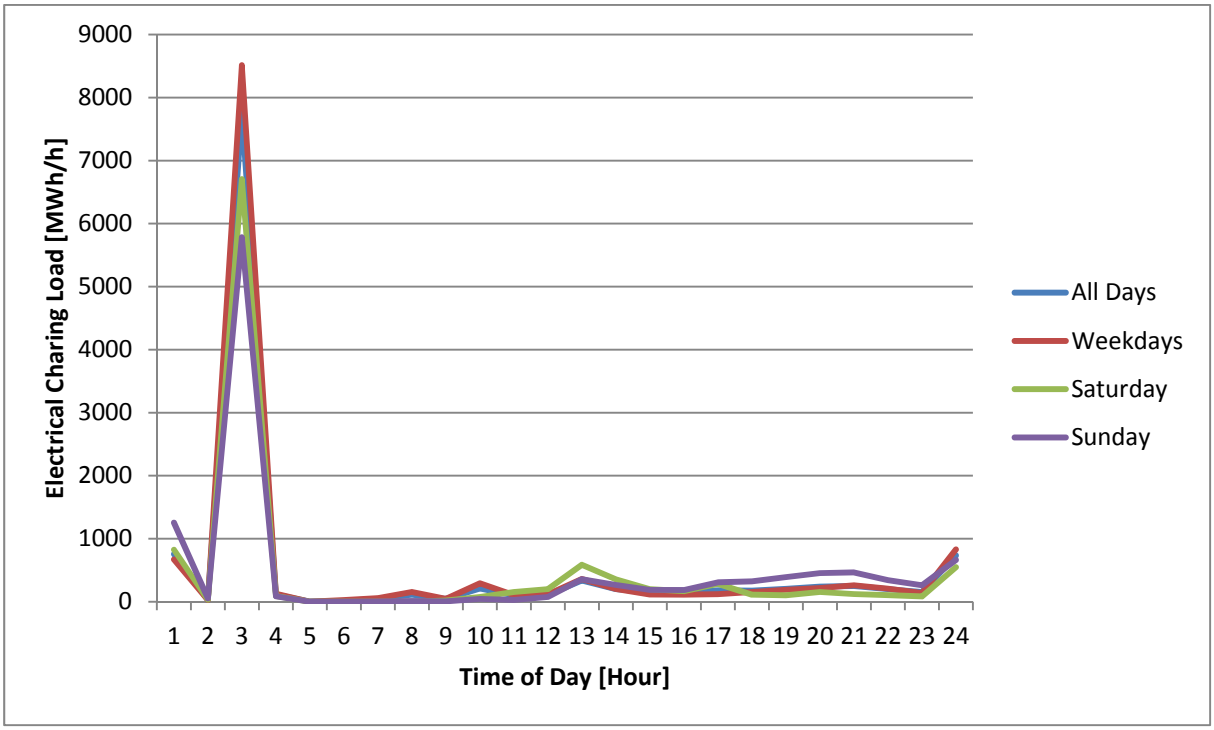

Figure 3-44 Electrical Load of 11.04kW Spot Price Based Charging All Day in Norway

The spot price based charging is set to minimize the total charging cost while the daily energy consumption should be recovered before 6 am of the next day. Therefore, most of the charging happens at night during the hours with the low spot prices and results in the high charging load at that time slot.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-14 shows the peak electrical charging loads of spot price based charging all day with different charging rates in Norway.

Table 3-14 Peak Load of Spot Price Based Charging All Day in Norway

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	3.46	4.93	8.51
Saturday	2.98	4.19	6.70
Sunday	2.54	3.62	5.78

The electrical charging load curves of spot price based charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Norway are shown in Figure 3-45 to Figure 3-47 respectively. It is shown that the load pattern of spot price based charging at home is very similar to that of spot price based charging all day.

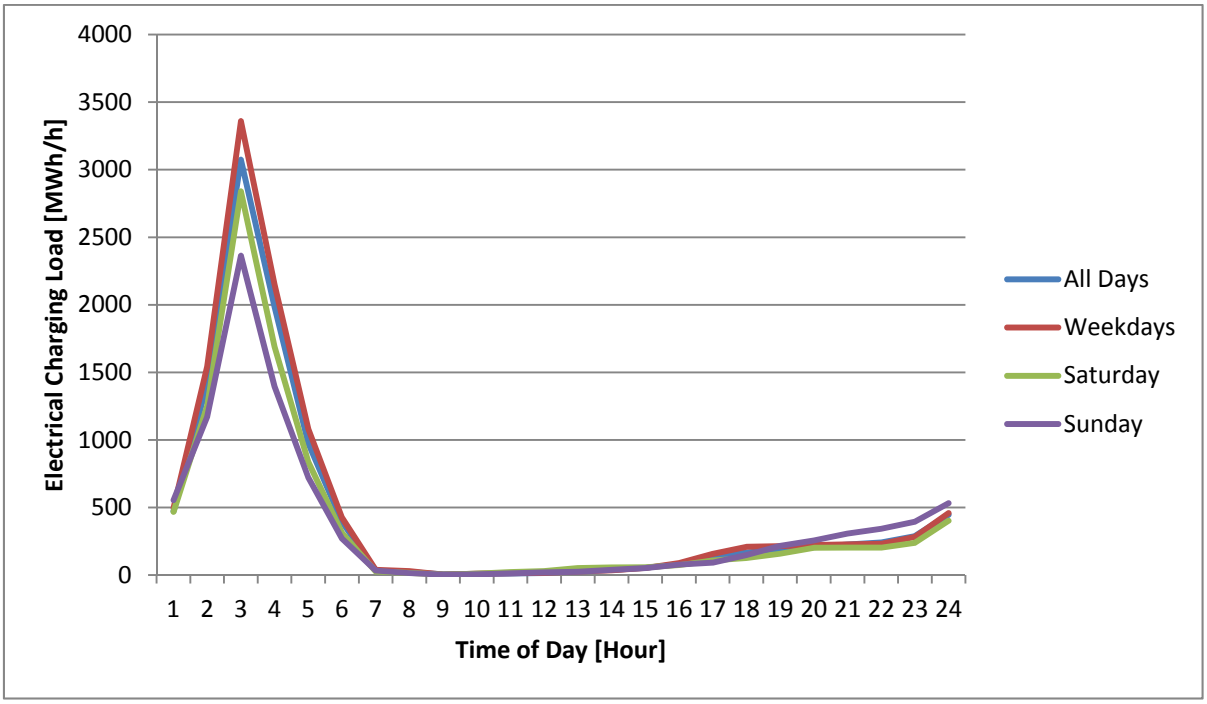

Figure 3-45 Electrical Load of 2.3kW Spot Price Based Charging at Home in Norway

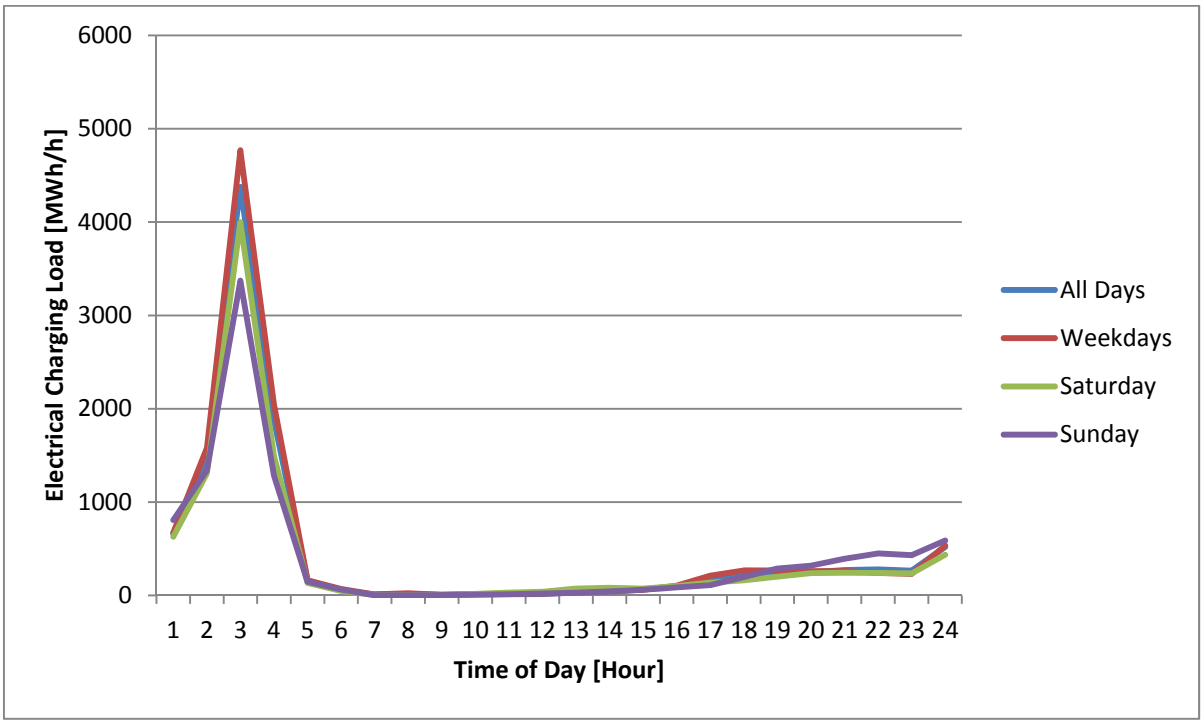

Figure 3-46 Electrical Load of 3.68kW Spot Price Based Charging at Home in Norway

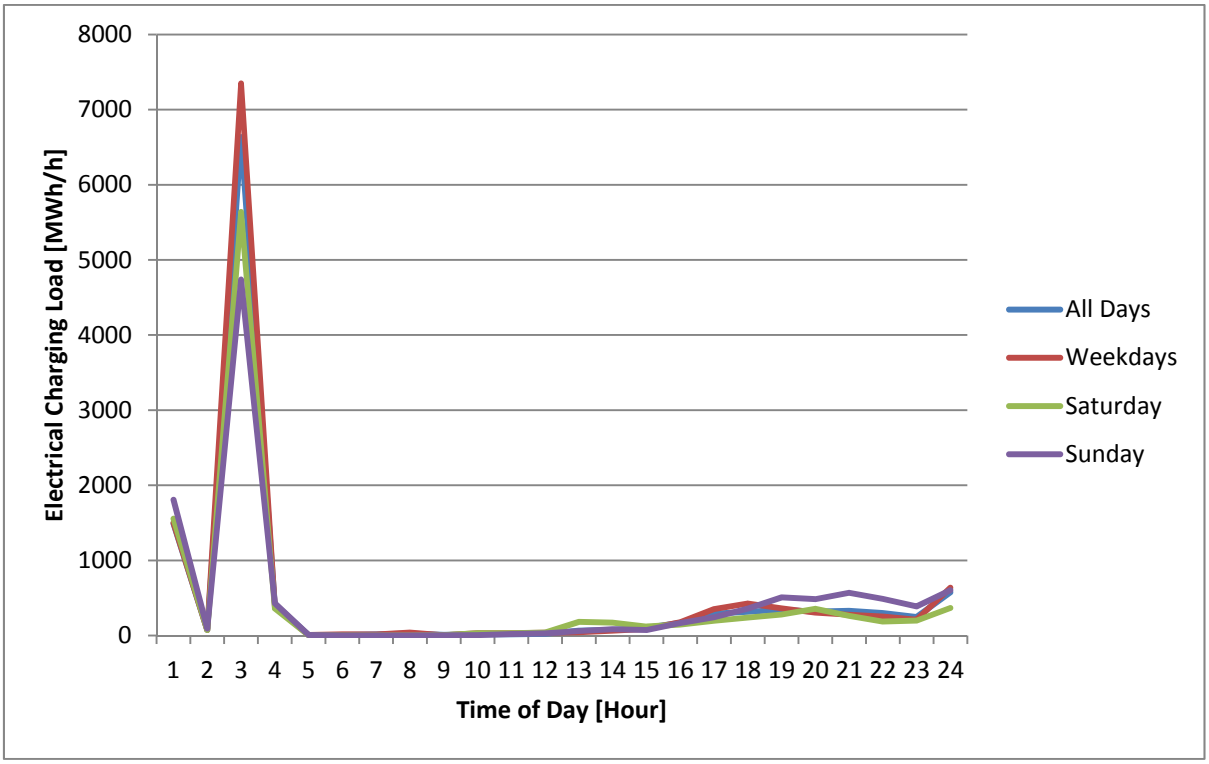

Figure 3-47 Electrical Load of 11.04kW Spot Price Based Charging at Home in Norway

Table 3-15 shows the peak electrical charging loads of spot price based charging at home with different charging rates in Norway. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-15 Peak Load of Spot Price Based Charging at Home in Norway

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	3.36	4.77	7.35
Saturday	2.84	4.00	5.64
Sunday	2.36	3.37	4.74

3.4.4 Impact of EV Charging on the Electric Load

Figure 3-48 shows the EV charging load curves of weekdays with different charging patterns based on the original electric load in Norway. The charging rate of all the charging in the figure is 2.3kW (1 phase - 10A). For both dumb charging all day and dumb charging at home, the peak charging load overlaps the peak hours of the original electric load in the evening during weekdays, which has worsened the case for the electric power system. However, the worst case happens in the timed charging scenario. Although the charging begins after 9 pm when the original electric load starts to decrease, the spike of the EV charging load is so steep that it results in a similar spike in the total electric load and the highest peak load of all the cases. The spot price based charging, to some extent, moves the majority of the charging demand to the low demand period of the electric power grid at night. Nevertheless, most of the charging congregates in the hours of low electric spot prices and leads to the high electric load in the corresponding time slot.

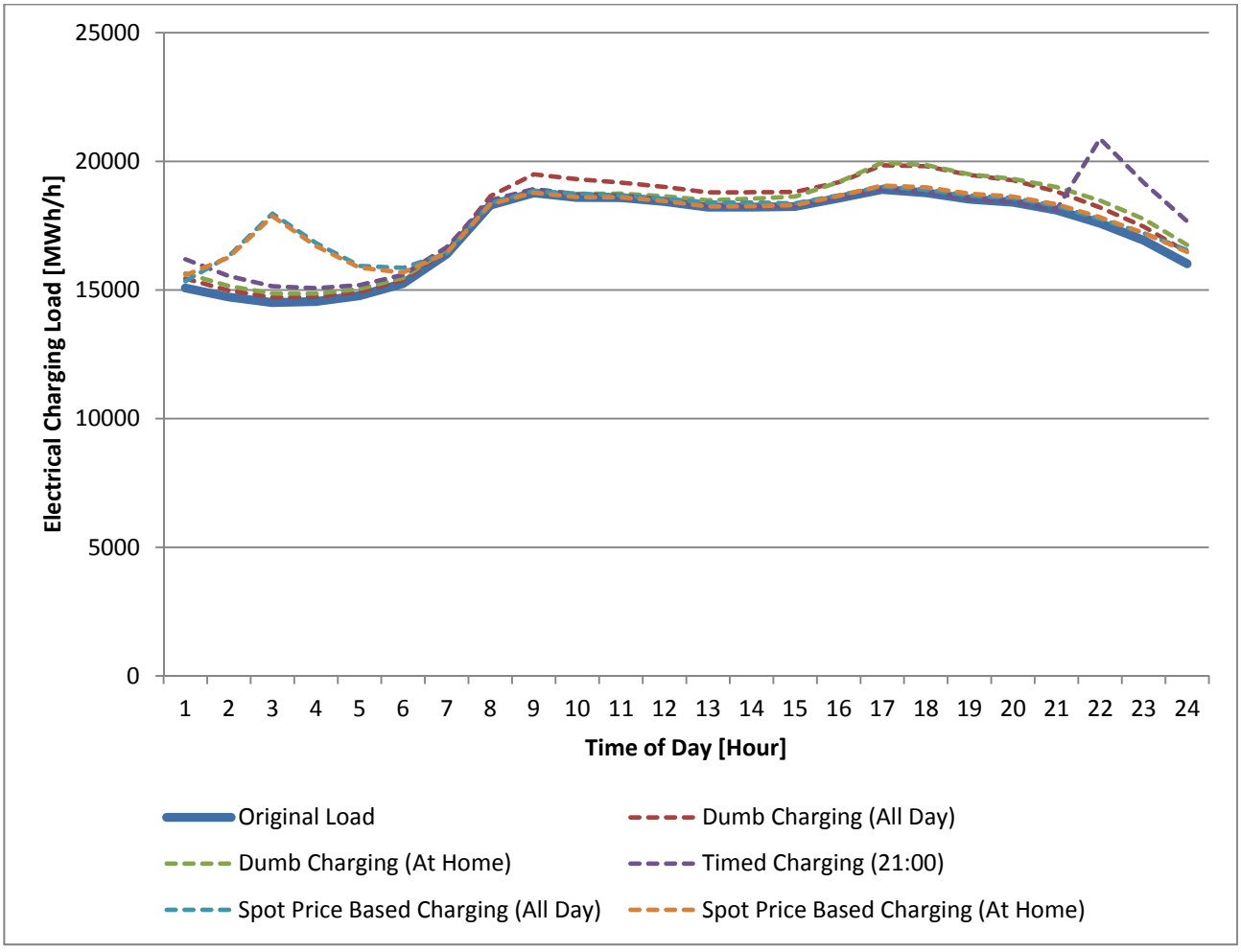

Figure 3-48 EV Charging Load of Weekdays with the Original Electric Load in Norway

3.5 Charging Analysis with High EV Penetration in Finland

3.5.1 Dumb Charging Analysis

The electrical charging load curves of dumb charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Finland are shown in Figure 3-49 to Figure 3-51 respectively.

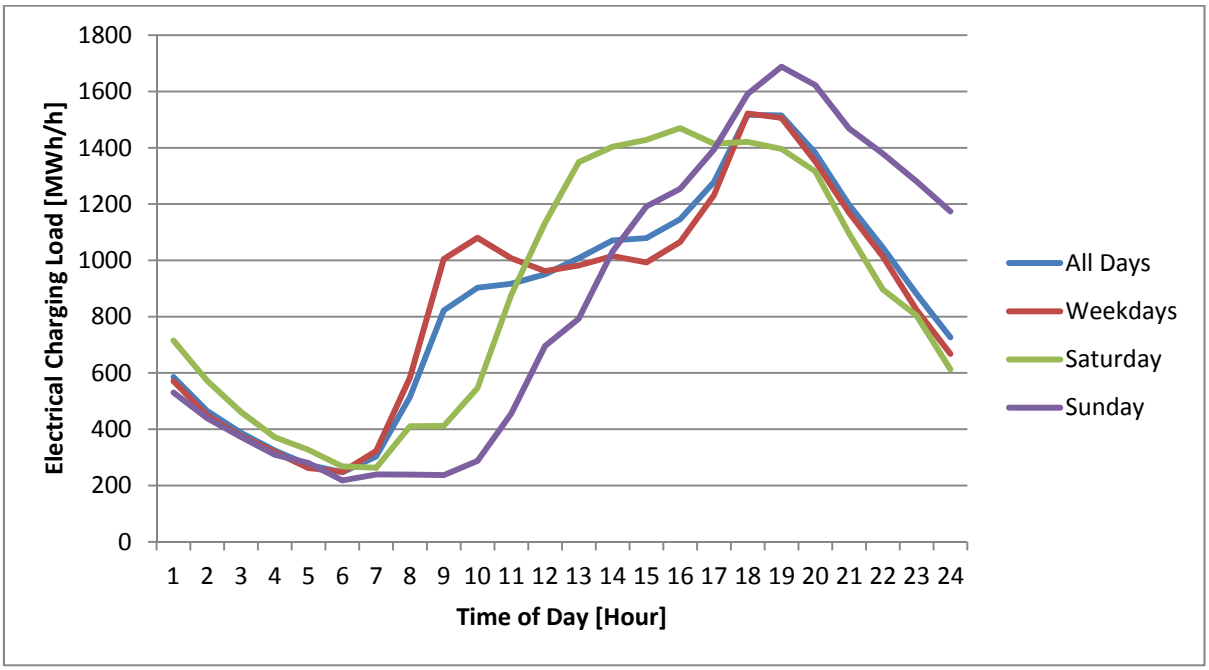

Figure 3-49 Electrical Load of 2.3kW Dumb Charging All Day in Finland

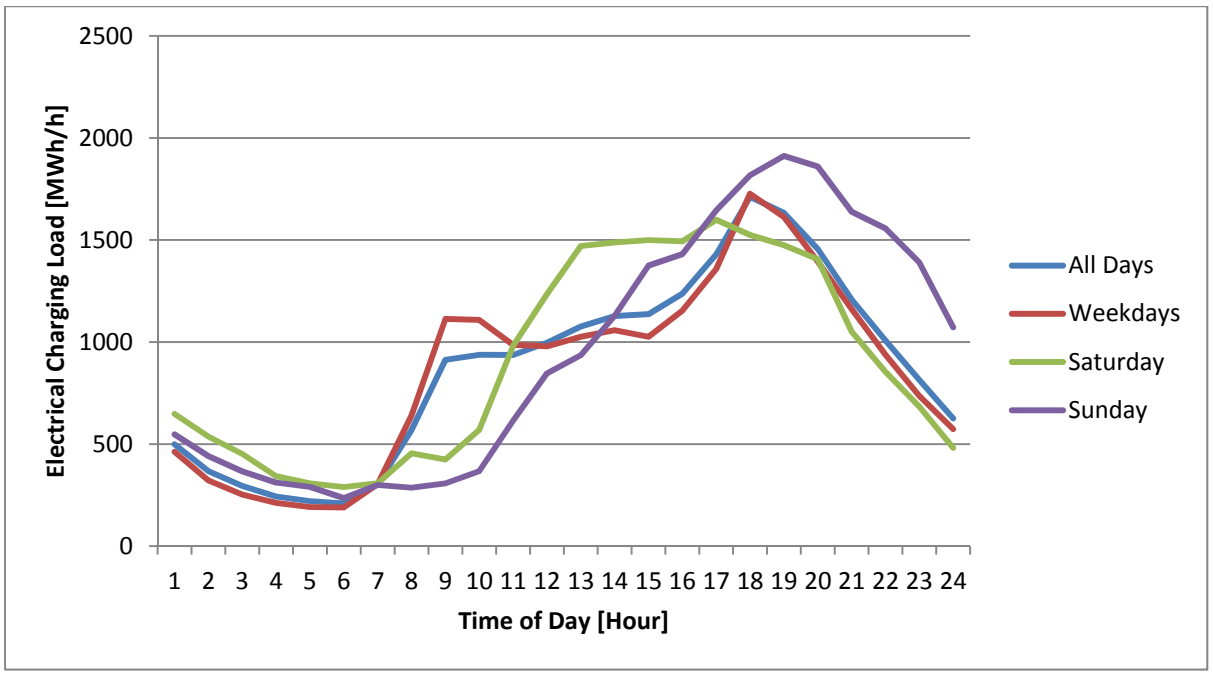

Figure 3-50 Electrical Load of 3.68kW Dumb Charging All Day in Finland

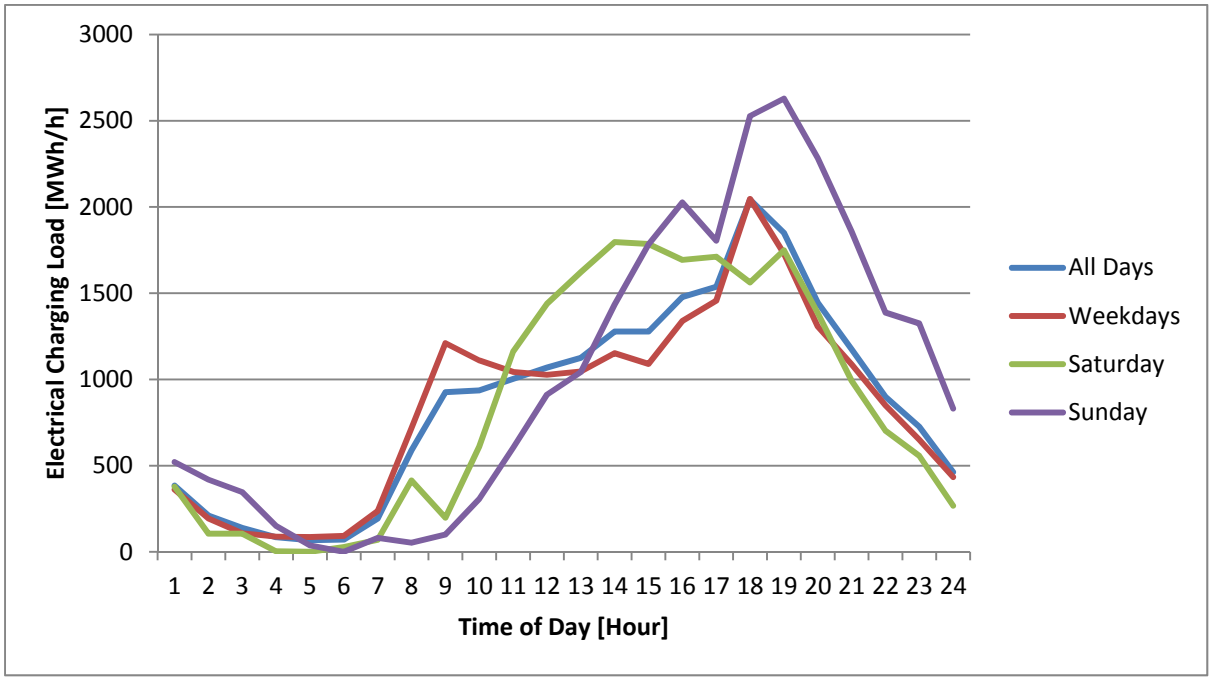

Figure 3-51 Electrical Load of 11.04kW Dumb Charging All Day in Finland

During the weekdays, there are two spikes in the EV charging load curves of dumb charging all day in Finland, one at 8-10 am in the morning and the other one at 5-7 pm in the evening. The highest load appears with the spike in the evening while the spike in the morning is lower obviously. The charging load on weekends starts to rise rapidly late in the morning and the majority of the charging happens in the afternoon and evening. The charging load patterns are in accordance with the driving patterns of Finland described in chapter 2.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-16 shows the peak electrical charging loads of dumb charging all day with different charging rates in Finland.

Table 3-16 Peak Load of Dumb Charging All Day in Finland

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.52	1.73	2.05
Saturday	1.47	1.60	1.80
Sunday	1.69	1.91	2.63

The electrical charging load curves of dumb charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Finland are shown in Figure 3-52 to Figure 3-54 respectively.

Different from the dumb charging load all day, the load pattern of dumb charging at home has no spike in the morning on weekdays. The charging load starts to rise at 3-4 pm in the afternoon and comes to the peak at around 5-7 pm when the most of the people are supposed to reach home from work.

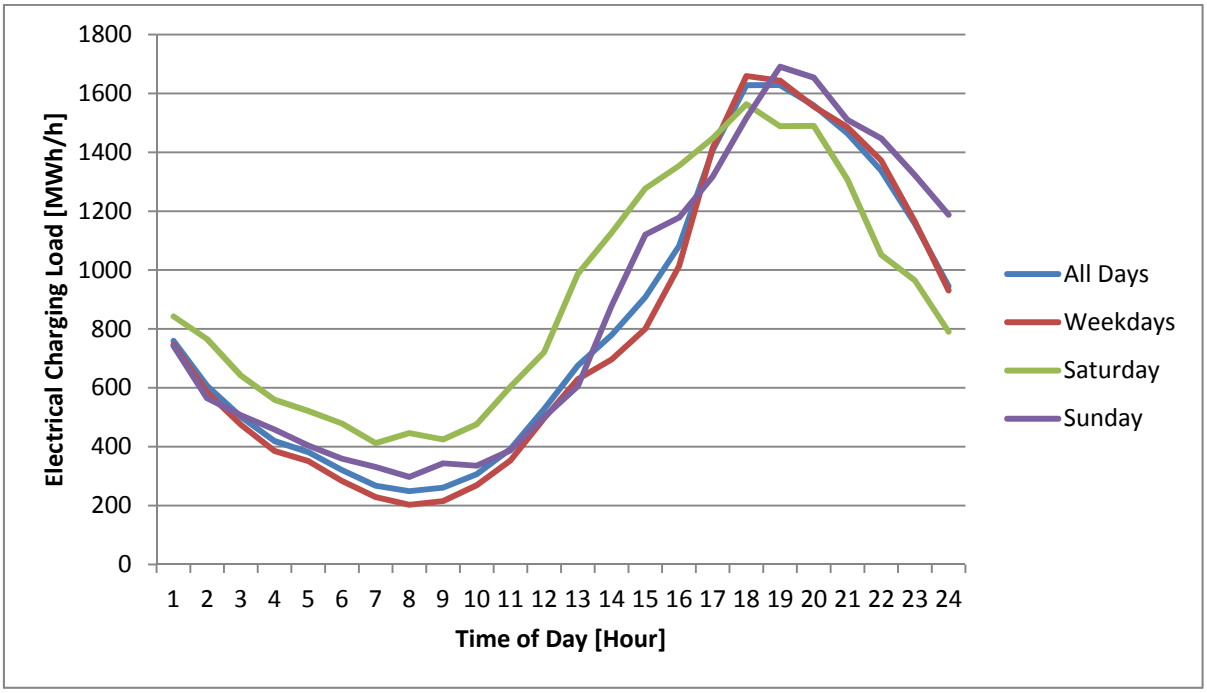

Figure 3-52 Electrical Load of 2.3kW Dumb Charging at Home in Finland

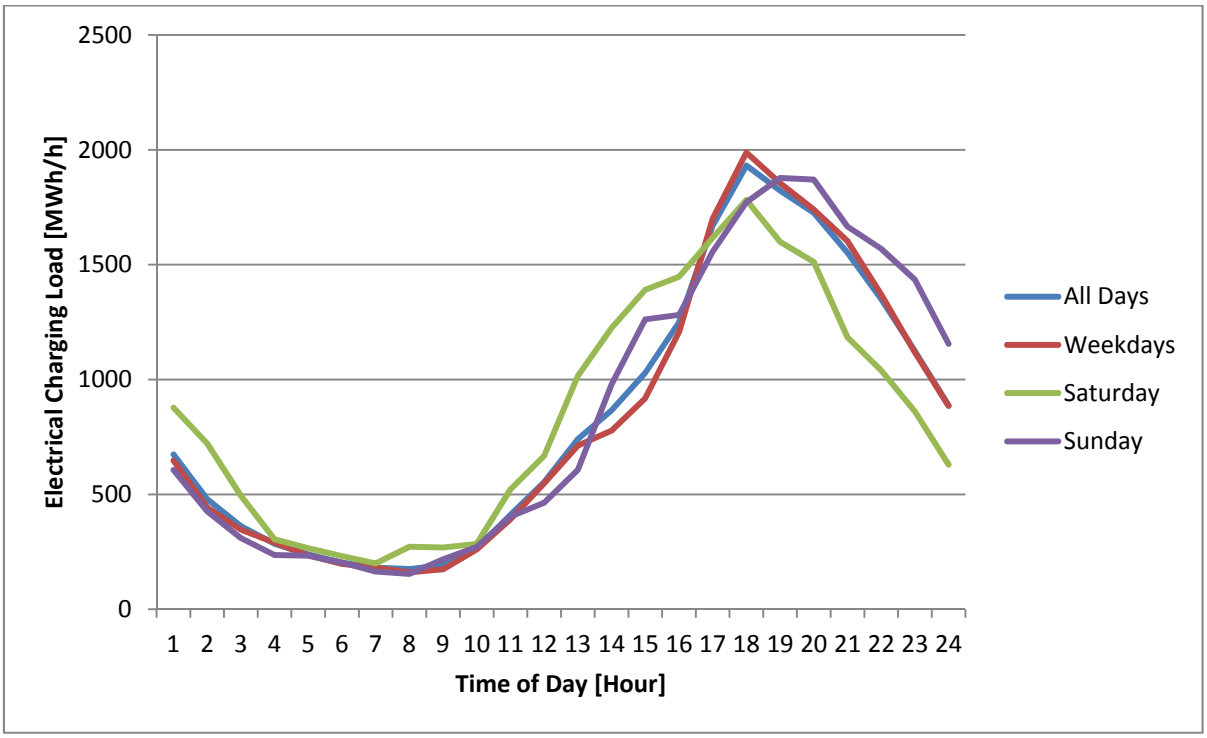

Figure 3-53 Electrical Load of 3.68kW Dumb Charging at Home in Finland

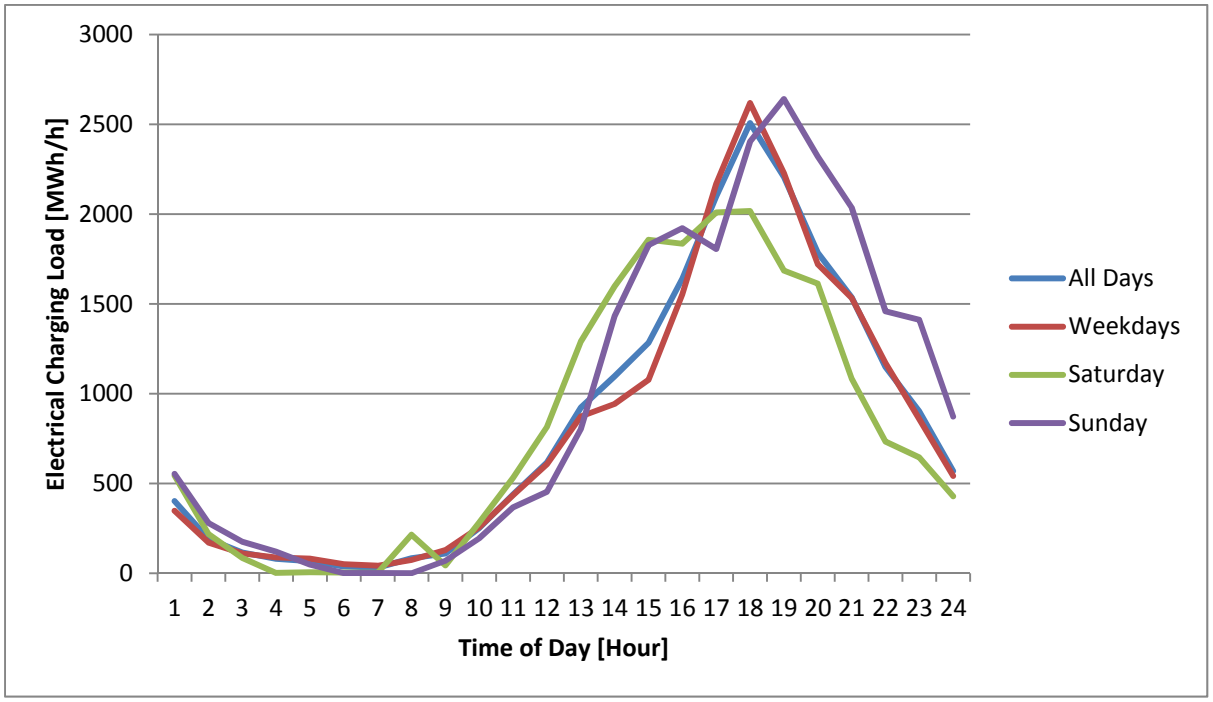

Figure 3-54 Electrical Load of 11.04kW Dumb Charging at Home in Finland

Table 3-17 shows the peak electrical charging loads of dumb charging at home with different charging rates in Finland. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-17 Peak Load of Dumb Charging at Home in Finland

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	1.66	1.99	2.62
Saturday	1.56	1.78	2.02
Sunday	1.69	1.88	2.64

3.5.2 Timed Charging Analysis

The electrical charging load curves of timed charging that all vehicles are charged during the parking period after 9:00 pm with the charging rates of 2.3kW, 3.68kW and 11.04kW in Finland are shown in Figure 3-55 to Figure 3-57 respectively.

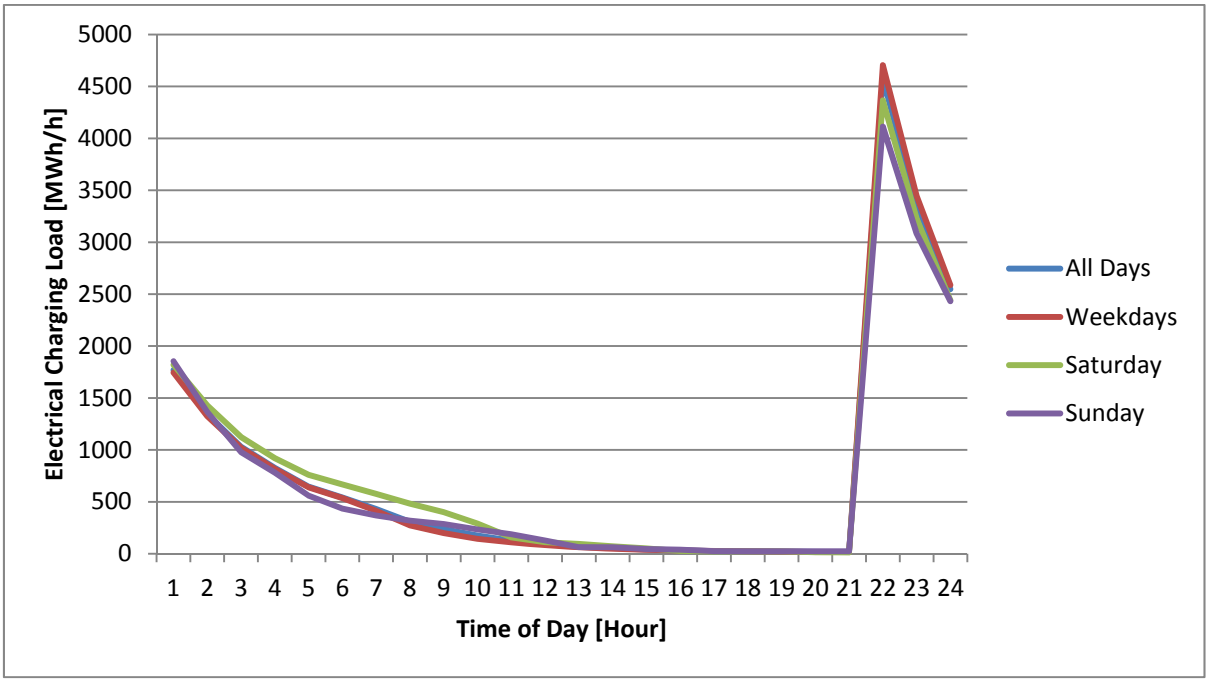

Figure 3-55 Electrical Load of 2.3kW Timed Charging in Finland

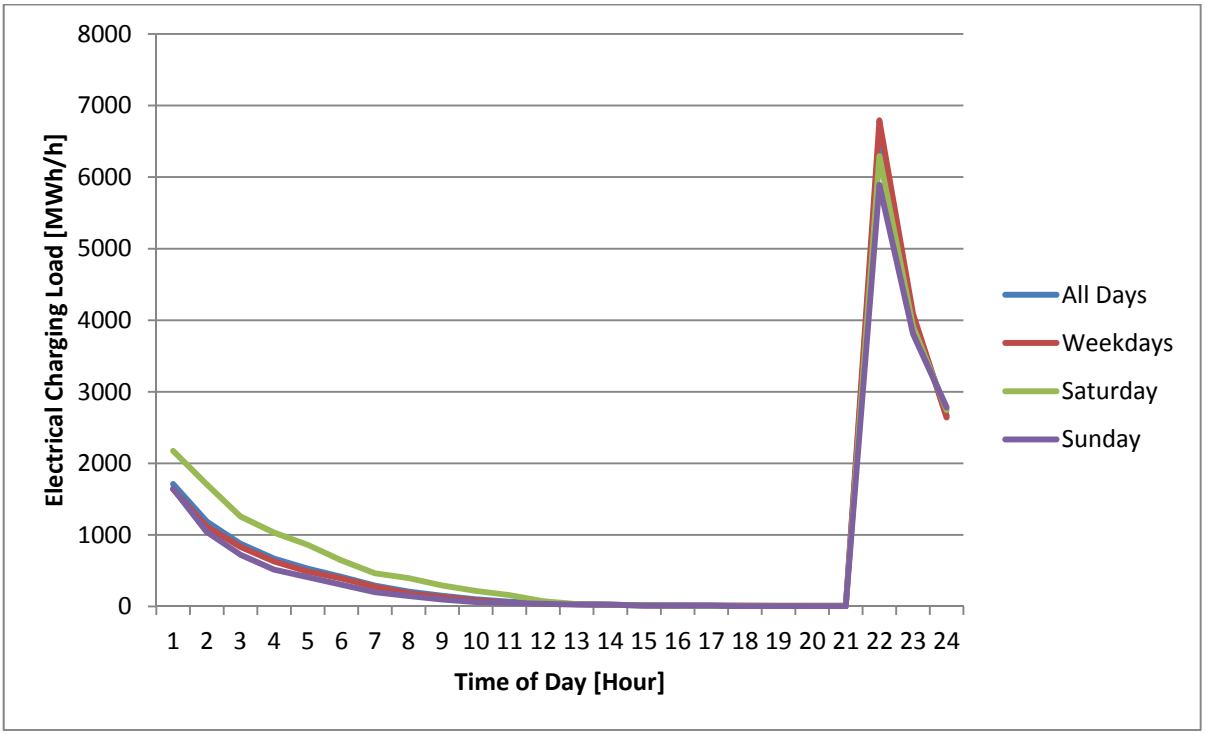

Figure 3-56 Electrical Load of 3.68kW Timed Charging in Finland

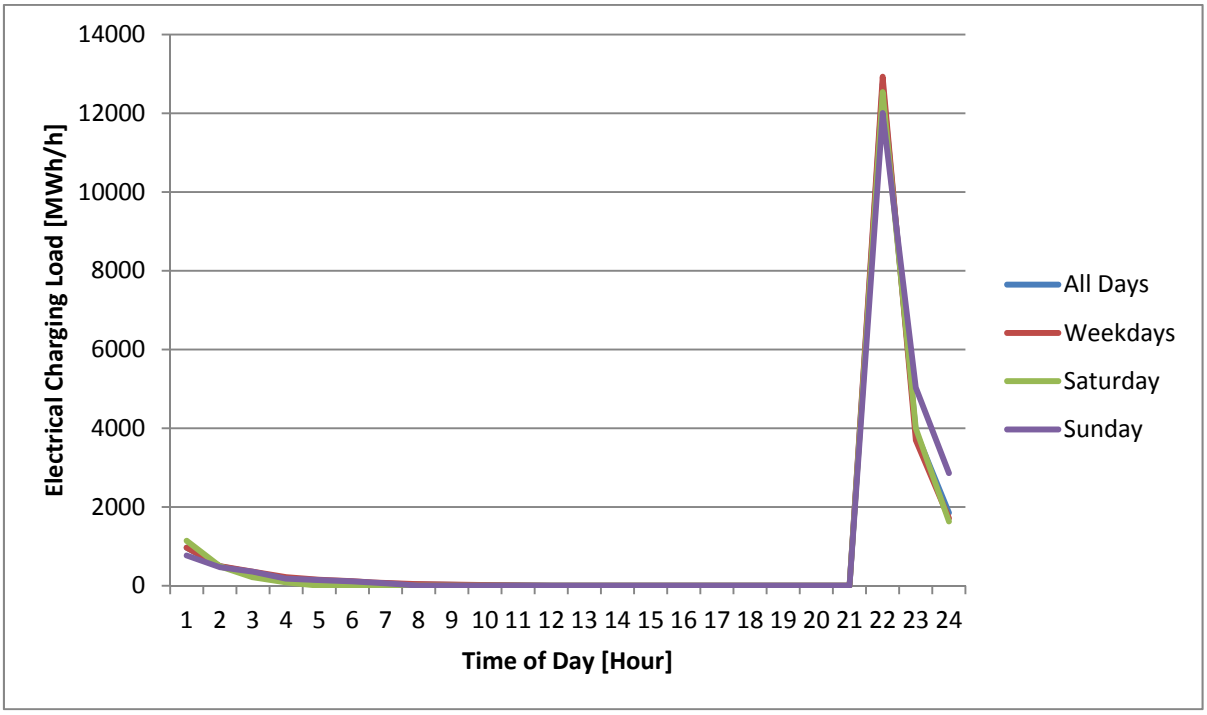

Figure 3-57 Electrical Load of 11.04kW Timed Charging in Finland

The highest electrical charging load shows at 9-10 pm when most of the charging starts. The charging load declines steadily afterwards. Similar to the situation of dumb charging, the electrical charging load curves show to be sharper with higher charging rates. Table 3-18 shows the peak electrical charging loads of timed charging with different charging rates in Finland. With timed charging, it is shown that most of the charging congregates in the short time slot after 9 pm, which makes a very steep spike in the charging load curve.

Table 3-18 Peak Load of Timed Charging in Finland

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	4.71	6.79	12.93
Saturday	4.37	6.29	12.54
Sunday	4.11	5.89	12.00

3.5.3 Spot Price Based Charging Analysis

The electrical charging load curves of spot price based charging all day with the charging rates of 2.3kW, 3.68kW and 11.04kW in Finland are shown in Figure 3-58 to Figure 3-60 respectively.

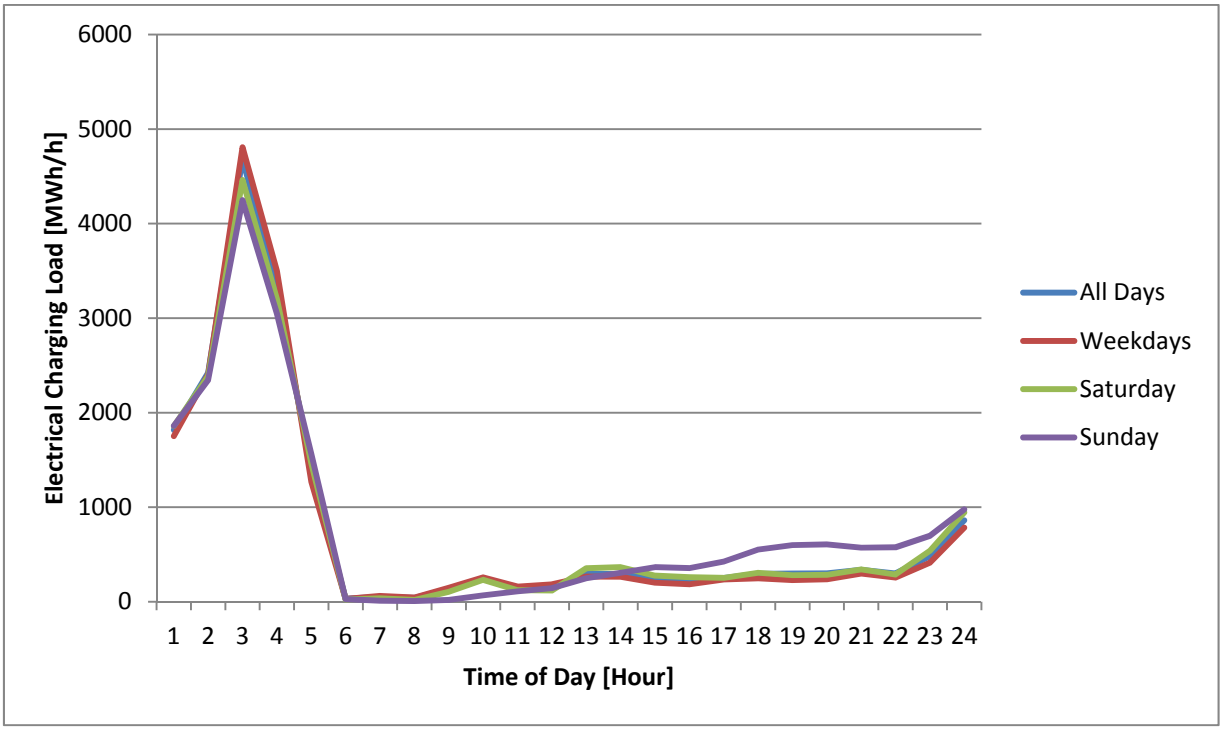

Figure 3-58 Electrical Load of 2.3kW Spot Price Based Charging All Day in Finland

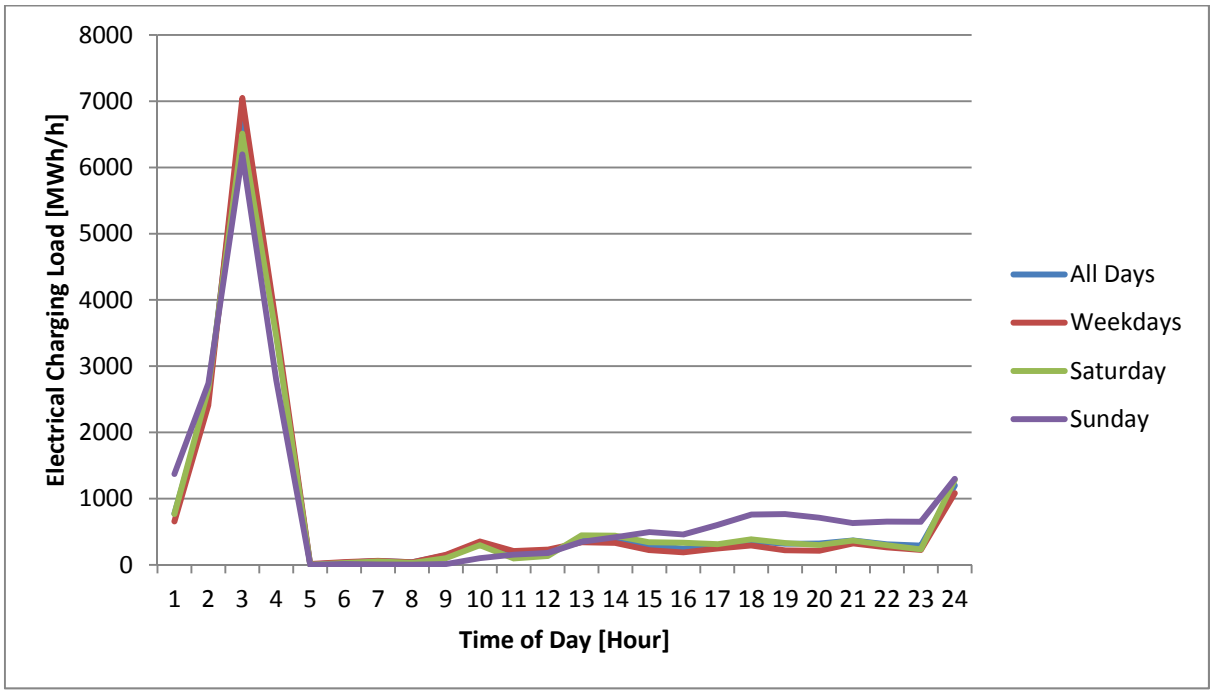

Figure 3-59 Electrical Load of 3.68kW Spot Price Based Charging All Day in Finland

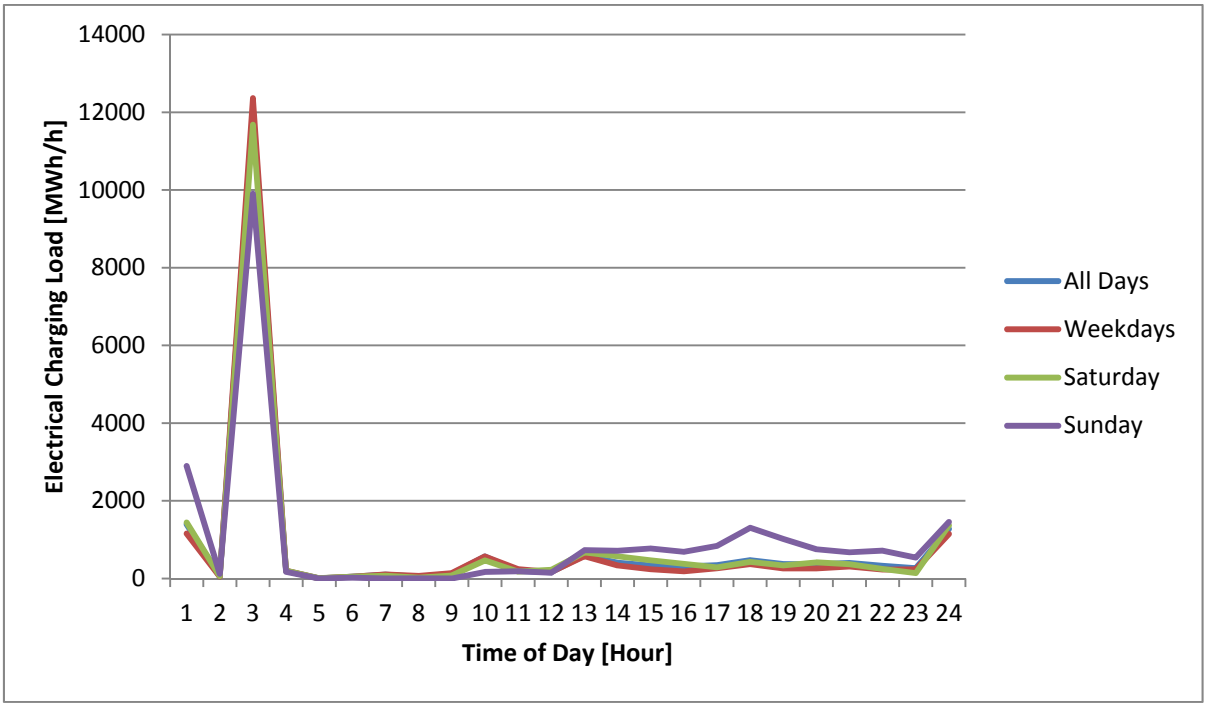

Figure 3-60 Electrical Load of 11.04kW Spot Price Based Charging All Day in Finland

The spot price based charging is set to minimize the total charging cost while the daily energy consumption should be recovered before 6 am of the next day. Therefore, most of the charging happens at night during the hours with the low spot prices and leads to the high charging load in the corresponding time slot.

With higher charging rates, the peak loads of the charging are higher and the electrical charging load curves show to be sharper. Table 3-19 shows the peak electrical charging loads of spot price based charging all day with different charging rates in Finland.

Table 3-19 Peak Load of Spot Price Based Charging All Day in Finland

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	4.81	7.05	12.36
Saturday	4.46	6.51	11.68
Sunday	4.25	6.19	9.90

The electrical charging load curves of spot price based charging at home with the charging rates of 2.3kW, 3.68kW and 11.04kW in Finland are shown in Figure 3-61 to Figure 3-63 respectively. It is shown that there is no marked difference between the load curves of spot price based charging at home and those of spot price based charging all day.

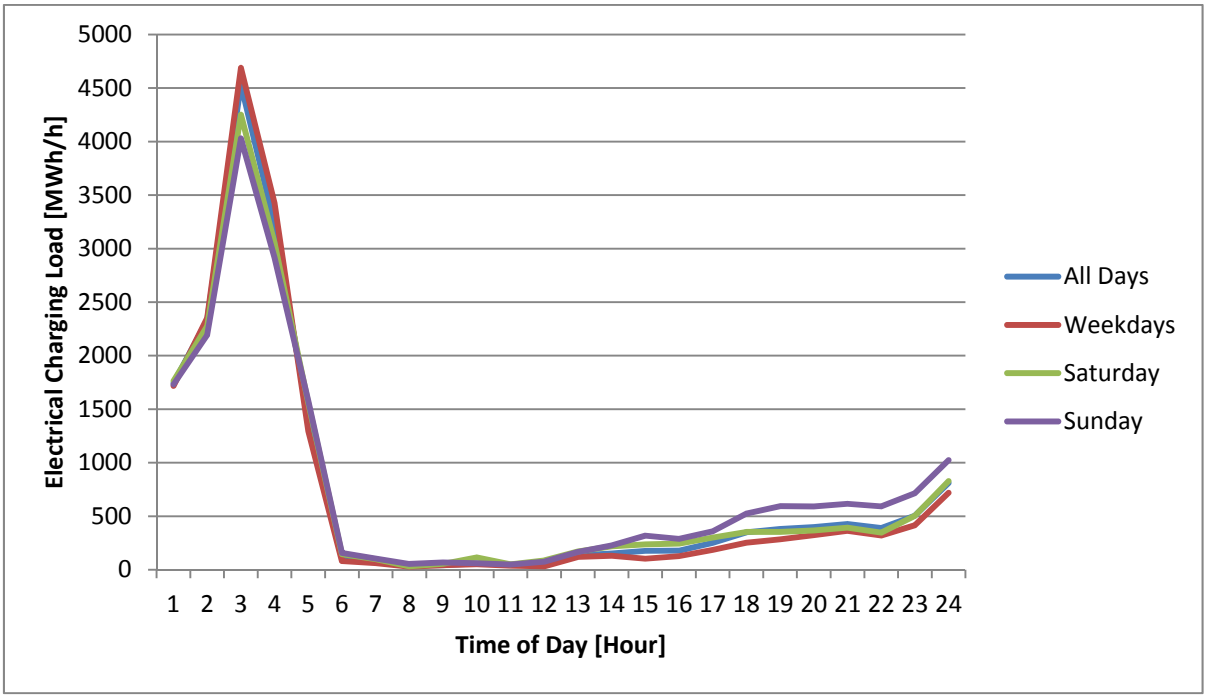

Figure 3-61 Electrical Load of 2.3kW Spot Price Based Charging at Home in Finland

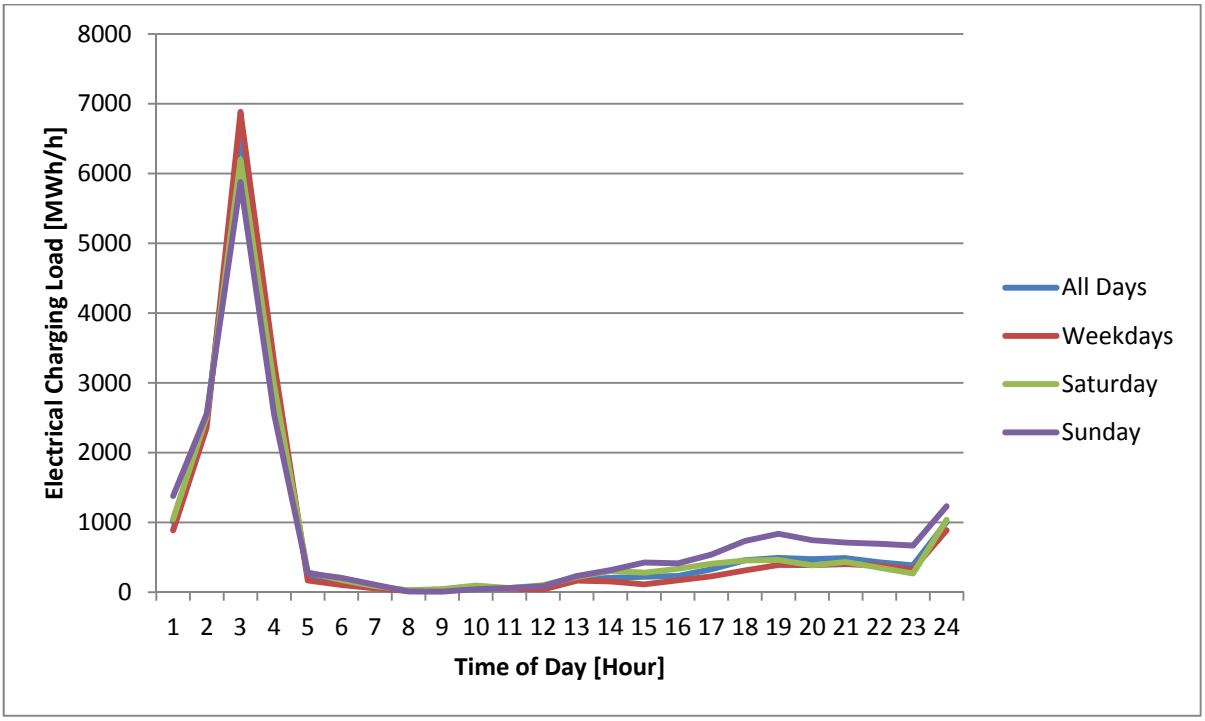

Figure 3-62 Electrical Load of 3.68kW Spot Price Based Charging at Home in Finland

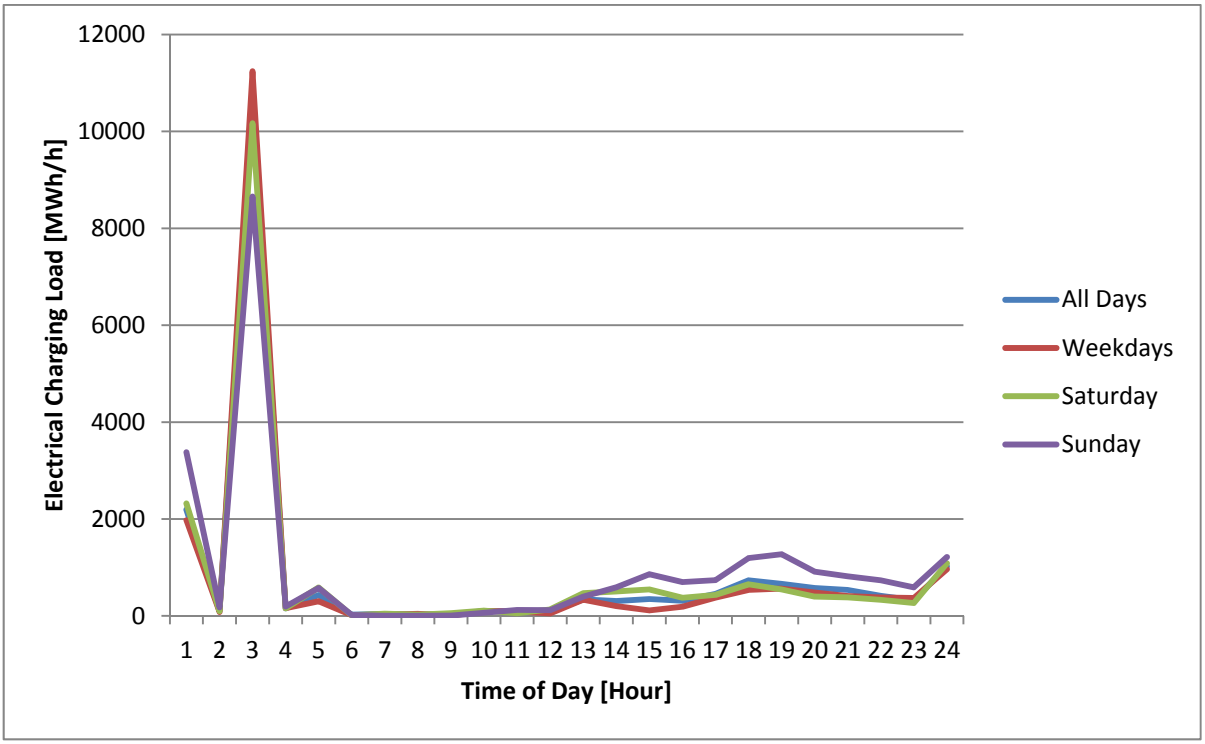

Figure 3-63 Electrical Load of 11.04kW Spot Price Based Charging at Home in Finland

Table 3-20 shows the peak electrical charging loads of spot price based charging at home with different charging rates in Finland. The figures are nearly the same as the case of spot price based charging all day. Again, the electrical charging load curves show to be sharper and the peak loads are higher with higher charging rates.

Table 3-20 Peak Load of Spot Price Based Charging at Home in Finland

	2.3kW - 1 Phase 10A [GWh/h]	**3.68kW - 1 Phase 16 A [GWh/h]**	**11.04kW - 3 Phase 16 A [GWh/h]**
Weekdays	4.69	6.88	11.24
Saturday	4.25	6.20	10.17
Sunday	4.03	5.88	8.66

3.5.4 Impact of EV Charging on the Electric Load

Figure 3-64 shows the EV charging load curves of weekdays with different charging patterns based on the original electric load in Finland. The charging rate of all the charging in the figure is 2.3kW (1 phase - 10A). For both dumb charging all day and dumb charging at home, the peak charging load overlaps the peak hours of the original electric load in the evening during weekdays, which has worsened the case for the electric power system. However, the worst case happens in the timed charging scenario. Although the charging begins after 9 pm when the original electric load tends to decrease, the spike of the EV charging load is so steep that it results in a similar spike in the total electric load and the highest peak load of all the cases. The spot price based charging, to some extent, moves the majority of the charging demand to the low demand period of the electric power grid at night. Nevertheless, most of the charging congregates in the hours of low electric spot prices and leads to the high electric load in the corresponding time slot.

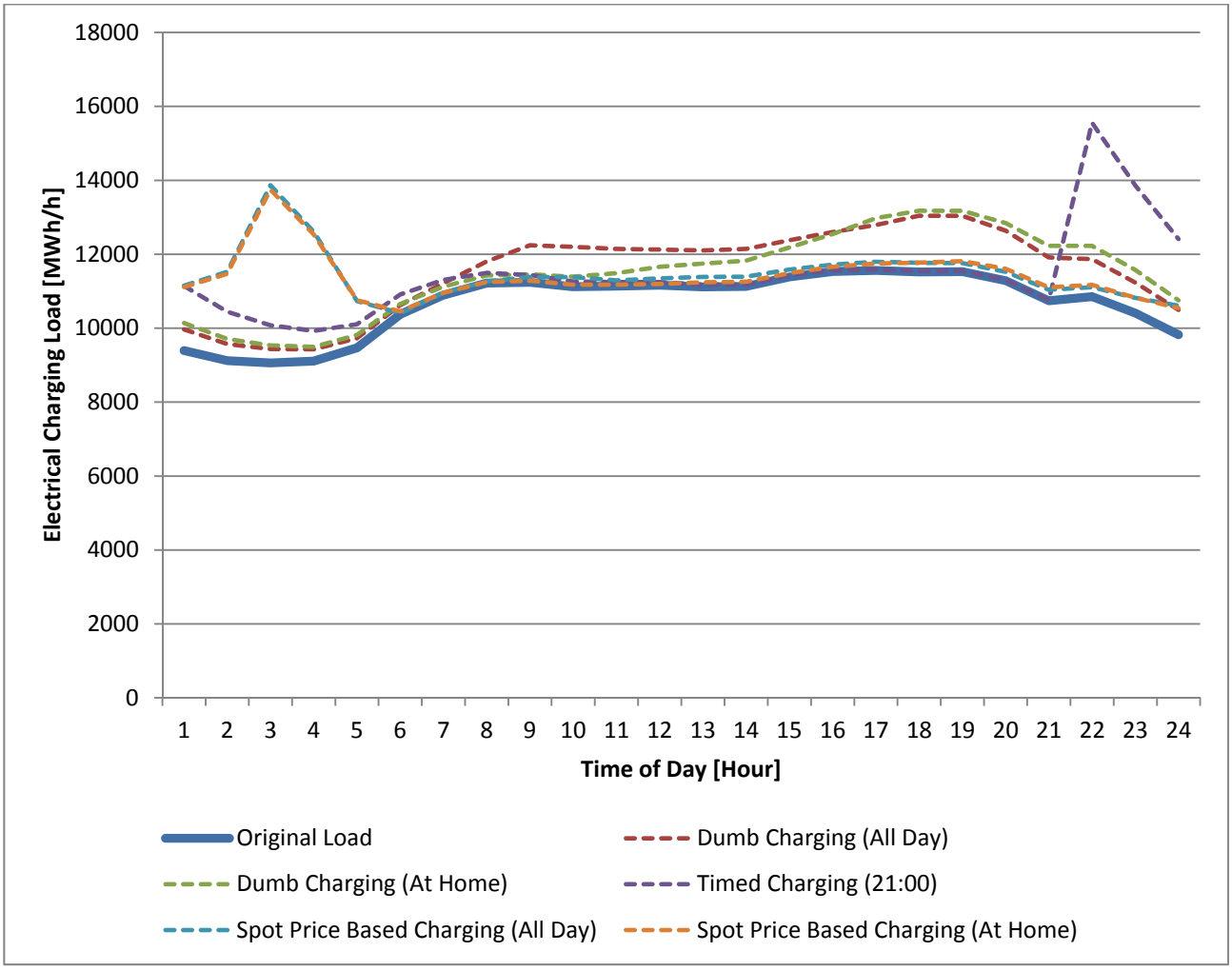

Figure 3-64 EV Charging Load of Weekdays with the Original Electric Load in Finland

3.6 Summary

The EV charging loads of the Denmark, Sweden, Norway and Finland have similar patterns. In all the four mentioned Nordic countries, the EV charging load is considerable if there is a high EV penetration level. With different charging patterns, the EV charging load curves are different from each other. For dumb charging all day, there are two spikes in the morning and in the evening after the rush hours when people go to work and go home on weekdays. However, for dumb charging at home on weekdays, the spike in the morning disappears and the peak load shows in the evening when people reach home. For timed charging, the peak load appears at 9-10 pm when most of the charging begins. The spot price based charging all day and the spot price based charging at home share similar charging load patterns. Most of the charging takes place at night during the hours with the low spot prices and results in the high charging load in the corresponding time slot.

Table 3-21 shows the peak loads of the EV charging with a charging rate of 2.3kW on weekdays in Denmark, Sweden, Norway and Finland.

Table 3-21 Peak Load of the EV Charging with 2.3kW of Weekdays in the Nordic Region

Charging Patterns	Denmark [GWh/h]	Sweden [GWh/h]	Norway [GWh/h]	Finland [GWh/h]
Dumb Charging All Day	1.13	1.56	1.03	1.52
Dumb Charging At Home	1.24	1.67	1.07	1.66
Timed Charging	3.35	4.46	3.29	4.71
Spot Price Based Charging All Day	3.46	5.31	3.46	4.81
Spot Price Based Charging At Home	3.29	4.96	3.36	4.69

Besides the charging patterns, the rating of charging power has obvious impact on the EV charging load patterns as well. With higher charging rates, the electrical charging load curves show to be sharper and the peak loads are higher. Table 3-22 shows the peak loads of the dumb charging of weekdays with different charging rates in Denmark, Sweden, Norway and Finland.

Table 3-22 Peak Load of the Dumb Charging of Weekdays in the Nordic Region

Charging Rate	Denmark [GWh/h]	Sweden [GWh/h]	Norway [GWh/h]	Finland [GWh/h]
Dumb Charging All Day				
2.3kW – 1 phase 10A	1.13	1.56	1.03	1.52
3.68kW – 1 phase 16A	1.26	1.73	1.14	1.73
11.04kW – 3 phase 16A	1.44	1.98	1.26	2.05
Dumb Charging At Home				
2.3kW – 1 phase 10A	1.24	1.67	1.07	1.66
3.68kW – 1 phase 16A	1.51	2.02	1.30	1.99
11.04kW – 3 phase 16A	1.96	2.63	1.84	2.62

The EV charging loads with different charging patterns will have different impacts on the electric power grid. On weekdays the peak charging load of dumb charging overlaps the peak hours of the original electric load in the evening, which has worsened the case for the electric power system. Timed charging begins after 9 pm when the original electric load tends to decrease. However, the spike of the EV charging load is so steep that it generates a similar spike in the total electric load. The spot price based charging moves the majority of the charging demand to the low demand period of the electric power grid at night. Nevertheless, most of the charging congregates in the hours of low electric spot prices and results in the high electric load in the corresponding time slot.

4 Conclusions

This report focuses on the driving patten analysis and the EV charging analysis in the Denmark, Sweden, Norway and Finland. The driving pattern analysis is based on the National Travel Surveys of the four mentioned Nordic countries. Further, the EV charging profiles are studied with the detailed driving patterns accordingly. Different charging patterns and charing rates are also considered. The following conclusions can be drawn from the driving patten analysis and the EV charging analysis of the Nordic countries mentioned above.

1. The daily average driving distance of passenger cars in the mentioned four Nordic countries is in a reasonable range compare to the EV endurance. Most of the daily trips of the passenger cars are in the short distance range.
2. The EV charging availability has similar patterns for all the four mentioned Nordic countries. For the EV charging availability (All-Day) when only the driving periods are considered as the unavailable periods, the availability is relatively high for over 90% throughout the day. During the weekdays, there are two notable valleys in the morning and in the evening when people are supposed to go to work and go home. The EV availability (All-Day) on weekends decreases gradually during the morning and ascends again from the afternoon to the night.
3. The EV availability (At-Home) with home charging only shows different patterns from the EV charging availability (All-Day). On weekdays, the EV availability (At-Home) begins to decrease in the morning when people start to leave home for work, keeps on a low level during the daytime and increases again in the afternoon when people start to go home.
4. The EV charging loads of the four mentioned Nordic countries share similar patterns. The EV charging load is considerable if there is a high EV penetration level, which is the same for all the four mentioned Nordic countries.
5. With different charging patterns, the EV charging load curves shows different and the peak load appears in different periods. For all the charging patterns, high charging rates sharpen the electrical charging load curves and lead to high the peak loads.
6. The EV charging loads with different charging patterns has different impacts on the electric power grid. The peak charging load of dumb charging overlaps the peak hours of the original electric load in the evening on weekdays. Timed charging (21:00) generates a spike in the total electric load after 9 pm when most of the charging begins. The spot price based charging transfers the majority of the charging demand to the low demand period of the electric power grid at night. Most of the charging happens in the hours of low electric spot prices and lead to the high electric load in the corresponding time slot. However, in the real electricity market, if the majority charges at the same period, it will impact the spot price and the peak in the electric load will be smoothed out to some extent.

From the study in this report, an overview of the charging load with large scale deployment of EVs in the Nordic region is generated. However, there are some factors which are not included in this report, such as the stochastic characteristic of the driving patterns of passenger cars, the interplay of the massive EV charging load and the electric power grid, etc. Future work shall be done in these relate areas in order to achieve a deeper look at impact of the EV charging load to the electric power system.

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