Analysis on the Integration of Electric Vehicles in the Electricity Grid with Photovoltaics Deployment in Sweden

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Abstract: Increasing environmental pressure makes it significantly important to improve the share of renewable energy source in terms of sustainable development. Photovoltaic (PV) cells are one of the most promising technologies at present for utilizing solar radiation. However, the large scale of PV penetration with its character of intermittency may cause problems for the power system and requires a more complex power system control. Self-consumption is a feasible solution to reduce the negative impact of PV on the power system. On the other hand, Plugged-in electric vehicle which could get charged by the electricity from the grid is a potential load for the general household in the future since the introduction of electric vehicles (EVs) is critical for building a fossil-fuel independent transportation. The aim of the project is to investigate the effect on the power consumption profile when adding PV generation and electric vehicle load, as well as whether the introduction of electric vehicle will help improve the matching between electricity consumption and PV generation. This study is done on both an individual household scale and a national scale. Conclusion from the simulation is that home-charged EV accounts for a great deal of energy consumption for a single household and it could improve the national energy consumption to some extent if largely introduced into the power system. In addition, Home-charged EV without strategic control does not improve self-consumption of PV either for a single household or on a national scale.

Keywords: Sustainable Development, Electric Vehicle, Photovoltaics, Self-consumption

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Summary: Increasing environmental pressure such as climate change and fossil fuel supply limits makes it significantly important to improve the share of renewable energy source in terms of sustainable development. Photovoltaic (PV) cell is one of the most promising technologies at present for utilizing solar radiation. However, a large scale of PV penetration with its character of intermittency may cause problems for the power system, including voltage rise and component overloaded. Self-consumption is a feasible solution to reduce the negative impact of PV on power system through improving the match between the local electricity demand and distributed PV electricity generation. On the other hand, Plugged-in electric vehicle which could get charged by the electricity from the grid is a potential load for the general household in the future since the introduction of electric vehicle is critical for building a fossil-fuel independent transportation. The aim of the project is to investigate the effect on the power consumption profile when adding PV generation and electric vehicle load, as well as whether the introduction of electric vehicle will help improve the matching between electricity consumption and PV generation. This study is done both on an individual household scale and a national scale. Conclusion from the simulation is that home-charged EV accounts for a great deal of energy consumption for a single household and it could improve national energy consumption to some extent if largely introduced into the power system. In addition, Home-charged EV without strategic control does not help improve the match between electricity consumption and PV electricity generation either for a single household or on a national scale.

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List of abbreviations

BEV	Battery electric vehicle
EV	Electric vehicle
FCV	Fuel cell vehicle
HEV	Hybrid electric vehicle
PHEV	Plugged-in hybrid electric vehicle
PV	Photovoltaic
CSP	Concentrating solar thermal power
SCH	Solar thermal collectors for heating and cooling
V2G	Vehicle to grid technology
EPIA	European photovoltaics industrial association
IEA	International energy agency
IEA-PVPS	International energy angency-photovoltaics power system programme
REN21	Renewable Energy Policy Network for the 21st Century
kw	kilowatt
GW	gigawatt
MW	megawatt
kWh	kilowatt*hour
TWh	Terawatt*hour

1. Introduction

Fossil fuels account for 67.6 % of the energy source in the world while renewable energy only represents 3.3 % (REN21, 2011). Under the increasing pressure of fossil fuel supply limits and global climate change, it is significantly important to improve the share of renewable energy source in terms of sustainable development. Solar energy is considered as the most abundant energy resource on earth. According to IEA analysis, under extreme assumptions solar energy technology could provide up to one-third of the world’s final energy demand after 2060 (IEA, 2013).

Photovoltaic (PV) cell is one of the most promising technologies at present for utilizing solar radiation which provides 10000 times more energy to the earth than it needs annually (Swedish energy agency, 2012). However, large scale of PV penetration with its character of intermittency may cause problems including variable frequency, voltage rise and overloading for the power system and require more complex power system control (Schavemaker, 2008). Installing PV panels on the existing residential buildings are becoming interesting for households because its possibility to reduce the electricity consumption costs especially when the PV systems are connected to the grid (Munkhammar, 2012). In that scenario self-consumption is a feasible solution to reduce the negative impact of PV on the power system, which means that the local production is matched by the local consumption without a need to inject the electricity generated from PV to the grid for further distribution. In addition, it is also interesting to investigate self-consumption of PV electricity generation on the national level as it estimates how much PV could be used domestically and how much might be necessary to export.

On the other hand, the introduction of electric vehicle is critical for building a fossil-fuel independent transportation, one of the Swedish government‘s long-term visions for sustainable, resource-efficient and emission-free energy supply by 2050. Therefore, electric vehicle (EV) which could get charged by the electricity from the grid is a potential load for the general household in the future. Then it will be interesting to investigate the correlation between photovoltaic electricity production and electric vehicle electricity consumption within a household as well as on the national level. Particularly, whether electric vehicle charging could help improve self-consumption of PV would be an interesting research question.

Swedish energy agency (2009) indicated that Sweden has a decent condition to deploy electrical vehicle in a large scale because of a strong distribution network and the plentiful energy resource which does not contribute for carbon emission. Previous study (Widén & Munkhammar, 2011) proved there is a possibility for high penetration of PV in the Swedish power system. These studies affirm the practical values on a research of the possible interact between electric vehicles and PV in the power system.

1.1. Aim of the study

The aim of this project is to investigate the interaction between electricity use, electric vehicle electricity consumption and photovoltaic electricity production in a power system. Primary research questions include:

A. How is the implementation of PV and home-charged EV going to influence the residential or national load profile?

B. Will the introduction of EV be beneficial to maximize the self-consumption of PV?

This study is done on both an individual household scale and a national scale. Research on question A will indicate how much electricity PV could generate and how much electricity EV will consume when they are introduced in a household or on the Swedish national level. Research on question B will manifest how much residential or national electricity consumption will be matched by PV electricity generation and whether the introduction of EV charging will improve the level of matching between PV electricity generation and electricity consumption. In order to answer the two main questions, following questions have to be solved at first.

- What is the reasonable size for PV at household level?
- What are the reasonable parameters for EV at household level?
- What is the reasonable penetration level for PV and EV at national level?
- What is the level of matching between PV generation and electricity consumption?
- What is the level of matching between EV charging and PV generation?
- What is the proper way to measure self-consumption?

1.2. Outline

The significance of this project on sustainable development, and the current situation of PV and EV are researched and presented in chapter two of this report. Methodology regarding the modelling, data source and scenarios planning is given in chapter three. Chapter four demonstrates the primary results from simulations. Discussion based on the results is shown in chapter five followed with the conclusion in chapter six.

2. Background

2.1. Sustainable development

In 1987, United Nation defined sustainable development as development that meets the needs of the present without compromising the ability of future generation to meet their needs. This definition is one of the most recognised definitions for sustainable development, which is considered to be the central guiding principle for governments, private sector and organizations to pursue sustainable and environmentally sound development (United Nation, 1987).

Physical limit and environmental impact of fossil fuels are pressing issues related with sustainable development. Many predictions of oil reserves suggest that oil production will peak and then fall gradually with decreased supplies and increased price within a short time period. In addition, the burning of fossil fuels emits carbon dioxide which plays significant role in greenhouse effect and climate change. Other emissions regarding fossil fuel combustion, including sulphur dioxide, nitrogen oxides, fly ash and other suspended particles, can harm human health and the environment to a great degree (United Nation, 1987). Therefore, it is necessary to develop other clean and abundant alternatives for energy supply.

Renewable energy is considered to be one of important choice due to its dramatic market growth, vast supporting policies and cost reduction (REN21, 2013). According to encyclopaedia Britannica, renewable energy is usable energy derived form replenishable resources such as the solar energy, wind power and hydro power, geothermal energy, tidal energy and biomass (Encyclopaedia Britannica, 2011). Among these choices, solar energy is the most abundant resource on the earth, the amount of which hits the earth's surface in one hour is about the same as that consumed by all human activities in a year (IEA, 2012). In order to utilize solar irradiance, photovoltaics is one of the most promising technologies.

On the other hand, the vast deployment of electric vehicles that rely on electricity generation with low greenhouse gas (GHG) emission has great potential to reduce the consumption of petroleum and other high CO2-emitting transportation fuels (IEA, 2010), especially in Sweden where most of the electricity is generated from emission-free resource (Swedish energy agency, 2009).

2.2. Integration of photovoltaics in the power system

2.2.1. Properties of PV

Active solar technologies convert solar radiation directly into heat or electricity (Schavemaker, 2008, p.61). Photovoltaic (PV), concentrating solar thermal power (CSP) and solar thermal collectors for heating and cooling (SHC) represents three main solar active technologies (IEA, 2010, p.5).

PV coverts the energy from solar photons to a direct current based on the photovoltaic effect which is first reported by Bequerel in 1839 (Green, 1982). The fundamental components of a PV system are photovoltaic cells (also called solar cells) which are interconnected in series to make a photovoltaic module (or called solar panel). As a module can seldom provide enough electricity for a whole household, a number of modules are linked to form a PV array.

Figure 1: PV modules at the Angstrom Laboratory in Uppsala University
Photo: Joakim Munkhammar.

PV cells are typically categorised as wafer-based crystalline or thin film. Wafer-based crystalline PV cells could be made of single crystal silicon, multi-crystalline silicon or compound semiconductors. This kind of cells is most common PV technologies and accounts for 80 % in the market. However, thin film cells are made of extremely thin layers of semi-conductor materials (EPIA, 2012, p.44).

The power of a PV module generally ranges from several watts to several hundred watts depending on the size and efficiency of the module, as well as the solar irradiance (Munkhammar, 2012). At present, PV modules have efficiency about 16 % on average (IEA, 2010).

Peak power of a PV module is defined as the maximum power output under standard test condition (STC): irradiation of 1000 W/m^2, solar spectrum of AM 1.5 and module temperature at 25 ℃ (Luque & Hegedus, 2003). A PV module with a size of 10 square meters and efficiency of 16 % has a peak power of 1.6 kW. Because of the flexibility of a PV system, PV technology can be applied in many ways, including pocket calculators and centralized PV plants.

Regarding the setup of a PV system, Latitude, azimuth angels and tilting of panels are significant variables, which could influence the output of power from a PV system to a large extent. More factors influencing the design of PV systems are summarised by (Norton et al., 2011). Figure 2 revels the average PV generation in a day on the basis of a year together with average electricity demand of a household. The PV array in this example is located in Uppsala and has a size of 25 square meters. Figure 2 reveals that the coincidence between PV electricity production and electricity consumption is not optimal. This is obvious especially in the areas at high latitudes where generation and electricity load are negatively matched on both daily and seasonal scales (Widén & Wäckelgård, 2009).

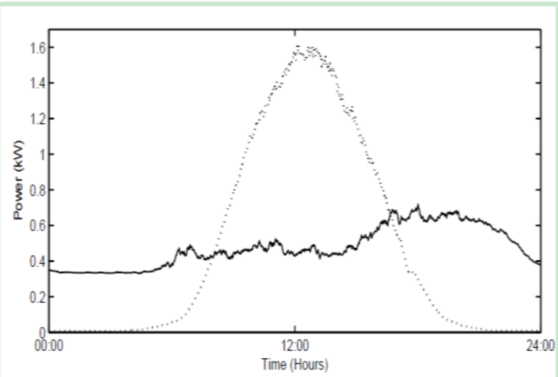

Figure 2: PV electricity generation (dotted) and household electricity consumption (solid) in a day for a household with two inhabitants are presented in this figure. The PV generation is average output over a year with a minute-based resolution from a PV array in the size of 25 square meters. The PV panel here is tilted with 45 degrees and facing south at Uppsala in Sweden. Peak power of the system is 4.3 kW if efficiency of PV module is assumed to be 17%.
Source: Munkhammar, 2012.

2.2.2. PV in the power system

IEA PVPS classifies PV systems into four categories (54):
A. Off-grid domestic
B. Off-grid non-domestic
C. Grid-connected centralized
D. Grid-connected distributed

Currently, Grid-connected systems C and D represent the vast majority of the installed PV systems. Though off-grid systems share merely 2 % of the total PV capacity in the world, they are gaining increasing interest especially in developing countries and rural areas and represent a large portion in some countries, including Australia, Israel, Norway as well as Sweden (REN21, 2012).

Since PV modules generate direct current, an inverter is needed to convert DC into alternating current (AC) when PV system is connected to electricity network. It could be one inverter integrated to one PV array or separate inverters connected to each string of PV modules. PV modules integrated with inverters are usually called as “AC modules” which could be connected to the electricity grid directly (PVPS, 2012).

In addition, the actual output of a PV system is generally much lower than its full capacity (IEA, 2010). In order to produce a significant amount of PV electricity over the year, high peak power will be a problem to handle with. With a high peak power, there would be a large amount of power injected to the grid at the end-user site. This could make grid components overloaded, increase the voltage and thus decrease the lifetime of equipments (Munkhammar, 2012). So as to reduce the negative impact of distributed generation, hosting capacity is defined as the maximum distributed generation penetration for which the power system operates satisfactorily (Bollen& Hassan, 2011). It is a power quality indicator regarding issues such as voltage rise, overloading and harmonics (Munkhammar, 2012). Hosting capacity is measured as a fraction of the acceptable injected power compared with the load on a yearly basis (Walla et. al, 2012). A sufficient hosting capacity is required when a great deal of distributed PV is introduced at the end-user site in the electricity network. In order to increase the hosting capacity for photovoltaic integration, there are mainly three methods apart from the traditional way of grid reinforcement which requires extra cost, including:

A. Adjusting settings for tap changer at the transformer substation
B. Active power curtailment by PV inverter
C. Reactive power control

Method B and C were indicated as the most effectual way to handle the problem of over voltage caused by PV penetration while the time intervals are limited and control ranges are narrow (Walla et. al, 2012). Self-consumption of the PV power is another option to settle the problem of inadequate hosting capacity (Munkhammar, 2012), which will be discussed specifically in the next section 2.2.3.

2.2.3. PV self-consumption

There is no common definition for PV self-consumption at this moment. For instance, Self-consumption is used by Munkhammar (2012) to represent the match between household electricity consumption and PV generation. In this scenario, higher level of self-consumption manifests that higher proportion of PV generation is consumed on-site, inside households, instead of being injected to the grid or curtailed. Therefore, the negative impact of PV generation in the distribution grid could be reduced and more PV generation could be utilized in this way, which means that the hosting capacity of distribution grid has been improved.

However, an inclusive definition of PV self-consumption has been concluded by SunEdison and A.T. Kearney (2011): "The possibility for any kind of electricity consumer to connect a photovoltaic system, with a capacity corresponding to his/her consumption, to his/her own system or to the grid, for his/her own consumption and feeding the non-consumed electricity to the grid and receiving value for it."

This definition includes different types of consumers, PV systems and grid connections. The consumer types could be residential, industrial, agricultural or public, and the PV system could be roof-top or ground-mounted. Meanwhile, it does not require that the generation is physically nearby the consumer, and it is unnecessary for the consumer to own the PV system. Therefore, PV self-consumption in a broad sense could be either on-site or off-site. Off-site PV generation and transmission through the grid could be regarded as self-consumption as well if the generation is tied to a specific consumer. Consumers can control their consumption of the PV generated electricity through a contract with a third party. Additionally, the capacity of a PV system is not restricted by an arbitrary legal limit but dependent on the consumption need of consumer (SunEdison & A.T. Kearney, 2011). Key Variations of PV self-consumption concepts which accord with the above definition are summarized in figure 3.

Off-site self-consumption might not be beneficial to improve the hosting capacity since transmission through grid could also be considered as self-consumption. However, it is discussed by A.T. Kearney that self-consumption in a broad definition could enhance the grid stability strongly by improving the match between local demand and distributed generation through grid congestion visibility and strategic asset deployment (SunEdison & A.T. Kearney, 2011). In this sense, self-consumption in a broad way is accordant with the concept used by Munhammar (2012), both of which aims to reduce the grid impact of PV penetration by enhancing the match between local demand and PV generation.

For the study at the household level in this project, self-consumption of PV refers to the level of matching between the household electricity consumption and PV electricity generation. For the study at the national level, it represents the level of matching between the national electricity consumption and PV generation. As the national scenario is a complex system, PV self-consumption with an inclusive definition is more consistent with the real situation. Though the grid benefits are not necessarily to be achieved by improving the self-consumption on the national level, it is possible to estimate how much PV generation could be matched with the national electricity consumption and how much might be necessary to export by researching on the PV self-consumption on the national level. This is an interesting research question as PV has a great potential to be applied in a large scale in Sweden in the future.

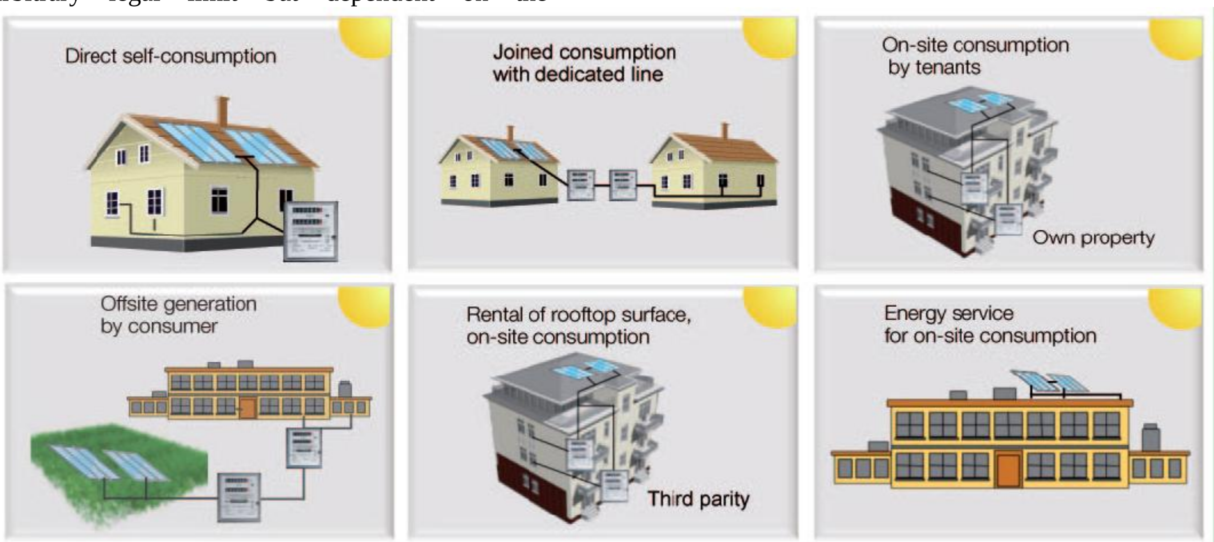

Figure 3: Variations of PV self-consumption. Source: SunEdison & A.T. Kearney, 2011

2.2.4. PV in the world

While renewable energy gains an increasing attention due to its significant environmental benefits, PV developed fastest among all the renewable energy technologies in terms of the growth rate of installed capacity in recent years (REN21, 2012). In

2011, the global growth rate of installed PV capacity reached 74% with an increment of 30 GW (REN21, 2012). Nevertheless, a historic record of PV installation was set in 2012 with another 31 GW installed which makes the global PV capacity surpass 100 GW (EPIA, 2013). Figure 4 demonstrates the accumulated capacity for worldwide photovoltaic.

Germany remains as the top market of PV with 7.6 GW newly installed system and 32 GW in total. Other largest markets with an increasing capacity more than 1 GW in 2012 include China, Italy, US, Japan, France, UK and India (EPIA, 2013).

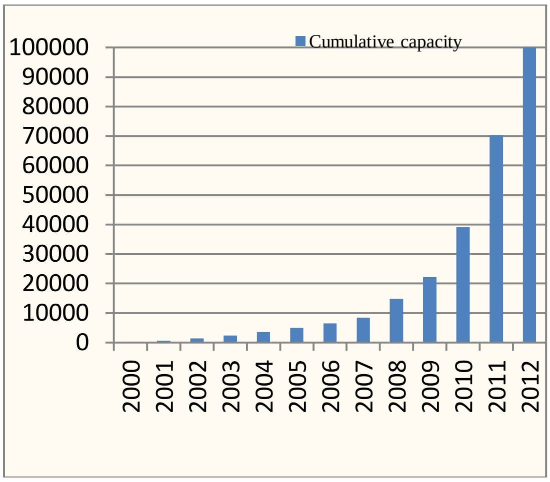

Figure 4: Cumulative capacity of PV installed in the world from the year 2000 to the year 2012. The unit of vertical axis is MW.
Source: EPIA, 2013

Governments over the world affirm the benefits of developing PV and relevant technologies. This is evident through substantially increased public expenditures on PV research and development (R&D) in the last decade. Public expenditure to support R&D in Japan, US, Germany and some other key countries has been doubled from 250 million USD in 2000 to 500 million USD in 2007 (IEA, 2010). This budget was invested for the whole value chain of energy generation ranging from raw material production to system balance. However, 75 % of the expenditure was spent on solar cell and PV module research and rest of it supported pilot projects and programs (IEA, 2010).

There are continuous endeavours on PV R&D from governments and industry aiming to promote PV as one of the main energy source. Some of the current efforts worldwide are presented in table 1.

Country / region	Plans
Europe	Three scenarios for solar share in the European electricity market proposed by Solar Europe Industry Initiative proposes: Baseline scenario (4%), Accelerated scenario (6%), Paradigm scenario (12%)
Europe	European PV Technology Platform's Strategic Research Agenda aiming to improve PV technology and cost-effectiveness
America	Integrated research intending to make PV electricity cost-competitive with traditional electricity by 2015
Japan	PV roadmaps towards 2030 (PV2030+) aiming to create sustainable PV business through the whole value chain
China	Solar growth strategy setting aggressive middle term targets
Australia	Initiative for 1000 MW solar generation
Brazil	Leading role in PV implementation for rural electrification

Table 1 Public efforts over the world on PV promotion
Source: IEA, 2010

PV module price reduced to a large degree because of the economies of scale associated with rising production capacities, technological innovations, competition among manufacturers, and a large decrease in the price of silicon. It was estimated that module prices fell more than 40% and the installed costs of roof-mounted systems fell by more than 20% in year 2011. Thin film prices decreased in past years (REN 21, 2012).

Though PV accounts for 0.1 % of global electricity generation at present, it is expected to supply 5 % of electricity consumption globally by 2030 and 11 % by 2050 according to the PV technology roadmap from IEA (IEA, 2010). Moreover, European Photovoltaic Industry Association (EPIA) provided a holistic vision on the future of solar electricity in European electrical system. Three scenarios were made for the share of PV electricity in 2030 in Europe (EPIA, 2012):

- Baseline scenario: 10 % of electricity demand is supplied by PV.
- Accelerated scenario: 15% of electricity demand is supplied by PV.
- Extreme scenario: 25% of electricity demand is supplied by PV.

2.2.5. PV in Sweden

Energy policy in Sweden is based on the vision that energy system should be socially, economically and ecologically sustainable and the security of supply should be guaranteed (PVPS, 2013a). To replace unsustainable fossil fuel and promote renewable energy, photovoltaic solar energy is one decent option. Sweden is a member country of International Energy Agency Photovoltaic Power System Programme (IEA PVPS), which was established in 1993 with a mission to accelerate the development and implementation of photovoltaic energy (PVPS, 2013a).

In 2009, a subsidy was allocated by Swedish Energy Agency to stimulate the installation of grid-connected photovoltaic system, which is able to cover up to 35 % of the system installation cost in 2013. This capital subsidy made grid-connected PV capacity in Sweden increase from 250 kW in 2005 to 9300 kW in 2011 (PVPS, 2013a). By the end of 2012, the cumulated PV capacity in Sweden reaches 24,000 kW and represents 0.01 % of the total electricity generation in Sweden (PVPS, 2013b). A figure for cumulative PV capacity is given below.

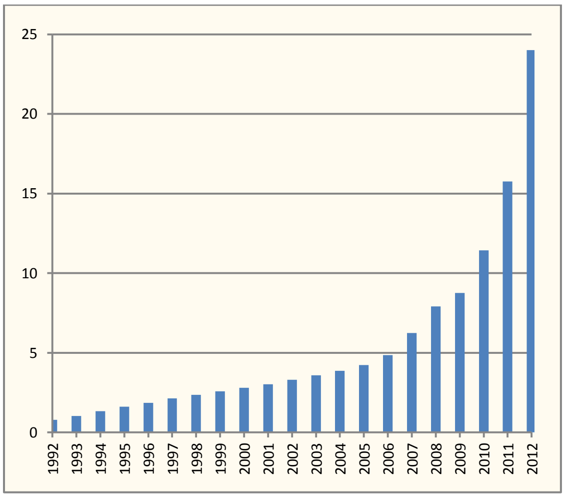

Figure 5: Cumulative capacity of PV installed in Sweden from the year 1992 to the year 2012. The unit of vertical axis is MW

Source: National survey report, 2012, p. 9

Apart from the capital subsidy from government, a net-metering scheme to promote grid-connected PV is under discussion and could be earliest introduced in 2014 (PVPS, 2013a). In addition, the interest from electricity utility companies in photovoltaic has grown to some extent (PVPS, 2013a). Some utility companies are buying surplus electricity from PV owners and some lunched compensation schemes or introduced net metering. For example, a local utility company in Sala-Heby municipality decided to buy the PV electricity from a local community with a price higher than the normal market price (PVPS, 2012).

Though located in area at high latitude, Sweden has a great potential for electricity generation from solar cells. According to EPIA, PV output per kW on optimally tilted panels in Sweden is 1050 kWh per year, which is comparable with that in Germany, 1085 kWh per year (EPIA, 2012, P107). This implies that Sweden has the same natural condition as Germany does to implement Solar PV. Furthermore, a study on widespread integration of PV at high latitude has been conducted by Widén and Munkhammar, which indicates that 370 Km^2 area regarding building surface in Sweden is suitable to settle PV systems and thus could generate electricity of 37 TWh per year (Widén & Munkhammar, 2012). Compared with the total electricity consumption in 2012 in Sweden, 139 TWh (PVPS, 2013b), the potential PV generation could supply 26.6 % of the total electricity demand.

2.3. Electric Vehicles

2.3.1. Categories of electric vehicle

An electric vehicle could be identified as any vehicle that uses electricity from a battery for part of or all of its driving energy. According to the different body structures and energy sources, EV could be categorized in several groups as discussed by Richardson (2013).

A hybrid electric vehicle (HEV) has both an electric engine and a combustion engine. There is an electric battery on board, which provides electricity to the power train and can be charged by the engine or through a process called regenerative braking. This improves the efficiency of the combustion engine but doesn't change the fact that the vehicle is fully powered by fuels when it's in motion.

A plug-in hybrid electric vehicle (PHEV) is similar to an HEV. However, PHEV has a larger battery and can be connected with electric grid, which enables PHEV charged with the electricity from grid and drive a long distance in all-electric mode.

A battery electric vehicle (BEV) is totally powered by electricity supplied by power grid and stored in a larger battery. Another type of EV is Fuel cell vehicle (FCV) which is powered by the electricity converted from the electrochemical reaction of fuels in the fuel cell, such as natural gas or hydrogen.

Electric vehicles considered in this project are mainly BEVs and PHEVs which can get charged from power grid.

2.3.2. Engine and battery

Compared with a conventional vehicle which has an internal combustion engine with an efficiency approximately at 30 %, electric vehicle has an engine with an efficiency as high as 80 % (Larsson, 2010).

Development of battery technology is under the focus of electric vehicle manufactures, although there are other choices to store energy, including fuel cell and super-capacitor (Swedish Energy Agency, 2009). Cost, capacity, safety remains the key challenges to introduce electric vehicle in a large scale (Swedish Energy Agency, 2009). Common battery types comprise Lead acid, Nichel metal hydrid and Lithium-ion. Among these alternatives, Lithium-ion battery gets increasing attention due to the advantage of higher energy density, power density and lifetime compared to other batteries (Grahn et al., 2011). A comparison of battery parameters is presented in table 2.

Energy density of battery is a critical parameter for the range of an electrical vehicle. Though lithium-ion battery has relatively high energy density, around 0.2 kWh/Kg, compared to other batteries, it's still much lower in comparison of liquid fuel, 12.5 kWh/Kg (Husain, 2011). This disadvantage makes batteries heavy and large to reach the same range as cars running on liquid fuel can achieve.

In order to guarantee the lifetime and performance of a battery, deep discharging should be avoid and impact of external temperature is another factor to take into account (Marano, 2009), especially in Sweden where the weathers varies dramatically from summer to winter.

Battery technology	Power density	Energy density	Life time	Price /kWh
	W/kg	Wh/kg	Discharges	DKK
Lead acid	<350	25-30	300-500	1000
Nickel Metal Hydride	250-1300	40-90	500-1000	2500
Salt-Nickel	170	120	>1500	2500
Lithium-ion-cobalt	500-2000	150-175	>1000	3500
Lithium-ion-phosphate	500-3000	100-150	>2000	2000

Tablex 2. Characteristics of current battery technologies
Source: (Swedish energy agency, 2009)

2.3.3. Charging

Electric vehicle could be recharged from the grid with different power. There are mainly three modes: slow charging with regular single-phase outlet, medium charging with three phase outlets and a higher power, rapid charging under even higher power (Grahn et al., 2011). The time to fully charge a battery depends on the chosen charging mode, battery capacity and the state of charge when it's connected, ranging from several minutes to several hours (Svensk Energi, 2010).

Slow charging is realistic to implement at present in Sweden because of the widespread engine heaters for cars in many houses, which can be used for charging with minor adjustment (Swedish Energy Agency, 2009). Medium charging could be constructed in both residential and commercial area but with a higher installation cost. However, rapid charging mode will function as collective facilities, similar to petrol stations (Morrow, 2008).

Charging at home or with public facility is an issue deserving further research to identify the situations which motive a driver to charge the car (Swedish energy agency, 2009). For example, the driver might not choose to recharge the car if the parking time is short.

Considering about the control method of charging, also called charge plan, it has been concluded by Richardson (2012) there are mainly three types: simple, delayed and smart charging. Simple charging represents the charging type that is not constrained. Delayed charging postpones the time for charging. Night charge for a cheaper electricity price is the example for delayed charging. The third type, smart charging, indicates some intelligent controls from system operator, which could be direct control on vehicles or indirect control through finance incentive (Richardson, 2012).

Figure 6: EV charging on a roadside.
Photo: Jingjing Liu

2.3.4. Electric Vehicles and the grid

A number of investigations have been done on the general impacts of plugged-in vehicles on the electricity grid. The results turned out to prove that the impacts could be either negative or positive depending on the different charging plans and models of the connection between vehicles and the grid (Richardson, 2013).

Hadley (2006) and Geth et. Al (2010) stated that simple charging plan will cause a growth on the peak load which needs additional capacity for generation and transmission. However, if delayed or smart charging is applied, vehicles constrained to charge at off-peak period have the potential to flatten the load curves and thus have no requirement for building extra capacity, which can increase grid efficiency (sustainable assessment, 2007; Kristofferson et al, 2011). Other effects of large-scale introduction of electric vehicles on the distribution grid are discussed over the topics about transmission choke point, transformer overload, voltage fluctuation, line losses and power quality (Green et al., 2011). According to the knowledge base from Swedish energy agency, Swedish electricity grid is well prepared for the penetration of large number of plugged-in vehicles in terms of stability (SEA, 2009).

Vehicle to grid technology (V2G) is another issue being discussed widely at present. Instead of only drawing electricity from the grid, V2G enables the vehicle provide energy stored in the battery back to the grid (Kempton & Letendre, 1997). A vehicle with V2G function is capable to offer services to power grid, including the regulation of equilibrium between demand and supply, peak power and the excess capacity required for spinning reserves (Kempton & Tomic, 2005). By charging when there is excess production and returning the energy to grid at peak-demand period, V2G system could assist to tackle with the intermittency of renewable energy (v2g, 2008).

2.3.5. Electric vehicle in the world

International energy agency (IEA) has a vision that more than 50 % of the passenger light duty vehicles sold in the world are BEVs or PHEVs in 2050 in order to achieve the goal of stronger oil dependency and 50 % reduction of CO_2 emission in 2050 on the basis of 2005 (IEA, 2011). This vision is presented through the blue map scenario of vehicle sales in figure 7. As part of this vision, BEV and PHEV will contribute to 30 % reduction of CO_2 emission related with light duty vehicles. Figure X shows the blue map scenario developed by IEA for electric vehicle in 2050. Similarly, Electric Vehicle Initiatives (EVI) which provides global forum for cooperation on EV development sets a goal that 20 million BEVs, PHEVs, and fuel cell vehicles will be registered by 2020 (IEA, 2011).

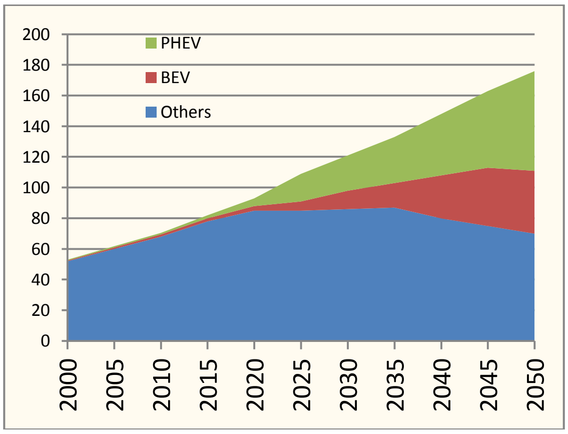

Figure 7: blue map scenario of global light duty vehicle sales per year
Source: IEA, 2011

With increasing awareness on the importance of BEV and PHEV for a more environment beneficial transportation, a large amount of resource has been assigned for the research and demonstration projects on electric vehicles. Examples of these projects include European Green Cars Initiative of European Union, 2.7 billion Euros to support EV diffusion in France, 1.1 billion Euros to promote EV development in China and the Test Program in USA which focuses on the technical development on battery, chargers and other components to support the deployment of electric vehicles. Countries involved significantly in the electric vehicle promotion comprise Japan, Israel, Germany, Great Britain, Spain, Portugal, etc (Hansen, K., Mathiesen, B.V., Connolly, D., 2011).

In the last 2 years, the number of BEV and PHEV on the road worldwide has increased dramatically. The global sale of BEV and PHEV in 2011 was 40,000 (IEA, 2012) and grew to nearly 120,000 in 2012 (Reportlinker, 2012). According to Bloomberg New Energy Finance, the total sale of BEV and PHEV in 2013 could be increased by 89 % to 225,000 (BNEF, 2013). Among the vehicles available in the market, GM Chevrolet Volt and Prius Plug-in from Toyota are typical examples for PHEV. For all-electric range vehicles, Nissan Leaf and Mitsubishi i-MiEV are models favored by consumers (Addison, 2013). Other models which could be delivered in the near future include Honda Fit EV, Tesla Model X Crossover SUV, Fiat 500e, BMW i3 all-electric city car, BMW i8 plug-in hybrid sports and Mercedes F-Cell (Addison, 2013).

2.3.6. Electric vehicles in Sweden

In 2009, Swedish government set a goal that the car fleet in Sweden should be independent of fossil fuel by 2030 (Swedish energy agency, 2009). At the same time, another target aiming to increase the proportion of renewable energy for transport is supposed to be achieved by 2020 (Hansen, K., Mathiesen, B.V., Connolly, D., 2011). Electric vehicle propelled by electricity free from fossil fuel is a promising tool to help approach these goals.

In 2010, a roadmap to promote green growth has been developed by Swedish government. Several issues regarding electric vehicle were mentioned, which include increasing the use of BEVs and PHEVs, exemption of taxation for EVs the first five years and 60 % reduction of benefit value for EVs (Hansen, K., Mathiesen, B.V., Connolly, D., 2011). The following year, 200 million SEK has been allocated by Swedish Energy Agency to support the research of electric vehicles and the relevant infrastructure in Sweden (Swedish Energy Agency, 2011). Under the ambitious goal on green transport, several projects focused on electric vehicles have been implemented in Sweden. Electric Car Procurement in Stockholm, E-mobility Malmo, and Fordonstekniska Försöks programmet (FFI) (Strategic Vehicle Research and Innovation Initiative) are examples. (Hansen, K., Mathiesen, B.V., Connolly, D., 2011).

Consistent with the global market, Sweden went through a significant rise in BEV and PHEV sales. During 2011, 181 out of 304,984 newly registered light duty vehicles were BEVs or PHEVs. However, the total number of BEVs and PHEVs sold in Sweden in 2012 was more than five times as the number in the year before, reaching 947 while the whole vehicle sale is slightly decreased (Bil Sweden, 2012). Data in 2012 reveal that BEV and PHEV account for 0.34 % of newly registered cars. Though the percentage increased to a large extent, the small proportion indicates that electric vehicles implementation in Sweden is in a small scale currently.

Elforsk, Swedish Electrical Utilities' R & D Company, has made a rough estimation on the number of electric passenger cars in Sweden based on different conditions of incentives in the near future, which is shown in the following table 3.

Number of electrical vehicles (BEV and PHEV) in the Swedish passenger car fleet			
Scenario	2010	2020	2030
Current control measures Merely remain current incentives	600	42,000	480,000
Mid-range Incentives continue to develop at the same rate as today The life cycle cost of electric vehicles is at parity with conventional vehicles in 2015	800	125,000	650,000
High-range The charging infrastructure is broadly accessible in cities, suburbs and some smaller towns. The life cycle cost of an electric vehicles is at parity with a conventional vehicle in 2015 and battery leasing is a realistic alternative	800	240,000	1780,000
Extreme range The demand for electric vehicles becomes extremely high and is limited in the short term only by the availability of vehicles	800	480,000	3270,000

Table 3: Elforsk's estimation on the number of electric vehicles in Sweden
Source: Swedish Energy Agency, 2009

The case of Extreme Range assumes there is a vast demand on electric vehicles and almost all the newly registered cars in 2030 are electric vehicles. This scenario could fulfil the target of Swedish government on fossil fuel independent transport. However it requires a large amount of financial or non-financial incentives and depends on the development of relevant technology and infrastructure to a great degree.

3. Methodology

The work in this thesis is based on investigating the correlation between household electricity use, home-charged plug-in electric vehicle electricity use and photovoltaic power production for different scenarios in Sweden. For the household electricity use and electric vehicle electricity, a stochastic Markov-chain model was used (Widén & Wäckelgård, 2010; Grahn& Munkhammar, 2012). The photovoltaic power production was estimated from high resolution solar irradiance data obtained from the Ångström laboratory (Munkhammar&Grahn, 2012). These models are described in section 3.1 and 3.2. As measures for the self-consumption of PV power, solar fraction and load fraction have been identified to investigate the coincidence between the solar production and electric vehicle energy consumption in section 3.3. Based on these models, data and measures, the effect on the load profile from EV integration into power system has been examined on both household level and national level. Four prime scenarios are planned in section 3.4 for relevant simulation.

3.1. Modelling energy consumption

3.1.1. Household energy consumption

Widén (2010) developed a discrete-time stochastic Markov-Chain model to estimate the general energy consumption from domestic activities. In order to simplify the model, a certain number of events which could represent the main domestic activities have been defined and the states number of these activities is fixed. Furthermore, it is assumed that each individual is engaged in only one activity at every time step.

A Markov-chain model is based on a stochastic process where for each time is occupied by a state. For each time-step there is a probability for transitioning from one state to another. These transition probabilities constitute a so-called transition matrix. The state of the next time step is only determined by the current one and has no relation to the previous states. The transition matrix for this particular Markov-chain model was calibrated with time-use data (Widén et al., 2012). For each activity, there is corresponding energy consumption related with it (Widén et al., 2012). From the Markov-chain model where each activity has an associated electricity use, average electricity use over a day or a year can be calculated. For more information about this model, refer to Widén's research (Widén & Wäckelgård, 2010).

3.1.2. EV energy consumption

Based on the Markov-chain model for energy consumption from residential activities, Grahn and Munkhammar (2012) made an extension from it to quantify the electricity use of a home-charging EV. In this extended model, driving the EV was added as an activity by assuming that for a certain probability p of the state 'Away' in the Widén-model the electric vehicle was used. The assumption was then that when the EV returned home from a trip it was instantly plugged in and charged until fully charged or used again. This concept will be shown with equations below. Another assumption is that EV has other energy sources such as fossil fuel or has stopped on the trip if the travel time of EV is longer than the time that battery can support (Munkhammar et al., 2012).

Critical parameters regarding electric vehicles have been defined as table 4 shows (Grahn et al., 2011):

Parameters	Notations
Load	$P_{EV}(t)$
State of charge	$SOC(t)$
Charging power	C^{Charge}
Maximum state of charge	SOC_{max}
Minimum state of charge	SOC_{min}
Average electricity consumption	C^{EV}
Vehicle usage probability	p_{EV}
Seasonal factor	$S(t)$

Table 4. Primary parameters for the electric vehicle charging model

Several important formulas for EV modeling are presented below (Munkhammar, 2012):

(1) The load of EV, $P_{EV}(t)$:

$$P_{EV}(t) = \begin{cases} C^{Charge} & \text{if charging} \\ 0 & \text{else} \end{cases} \qquad (3.1)$$

It should be noted that $P_{EV}(t)$ could be negative if EV is considered able to provide power to the grid. However, this situation is not included in this model.

(2) Energy level in the battery:

$$SOC(t+1) = \begin{cases} SOC(t) - C^{EV} * S(t) * \Delta t & \text{if consuming} \\ SOC(t) - C^{Charge} * \Delta t & \text{if charging} \\ SOC(t) & \text{else} \end{cases} \qquad (3.2)$$

The average electricity consumption power Cev multiplied by seasonal factor S(t) which represents the amount of electricity that has been consumed on the way. S(t) means there is seasonal difference on energy consumption because of heating or cooling.

(3) Boundary condition of SOC(t):

$$\mathrm{SOC_{min}} < SOC(t) \leq \mathrm{SOC_{max}} \quad (3.3)$$

The boundary condition of SOC(t) is to assure that the battery depleting is in a reasonable range and lifetime of battery could be guaranteed longer.

3.1.3. National electricity consumption

The data of Sweden's electricity use, which is around 141 TWh in 2011, is from NordPoolSpot (2013).

3.2. Modelling PV electricity production

For the simulations of this paper, solar irradiance data with high resolution which was obtained from a pyranometer located at the Angstrom laboratory was used. The data used here was collected for every minute of the whole year 2011. The electricity output of PV was calculated from the followed equation:

$$\mathrm{P_{pv}}\ (\mathrm{t}) = \theta * \mathrm{A} * \mathrm{G(t)} \quad (3.4)$$

P_{pv} : Power production from the PV module over time

θ: PV system efficiency, which has been set as 13%

A: PV area (m2)

G (t): the incident solar radiation (W/m2), which was measured in a panel with a 42- degree tilt by a pyranometer at the laboratory of Angstrom in Uppsala, Sweden. The time duration for the collected data is from1st January to 31th December, 2011. In order to match the data resolution of domestic, national and EV energy consumption, the resolution for PV radiation data was set as 1 minute based on average. Specifically, the PV module used in this project has a peak power of 168W per meter square.

3.3. Index for measuring PV self-consumption

Solar fraction of energy consumption (SF) and load fraction of PV generation (LF) are Two useful measures for estimating the level of self-consumption in this project. SF is defined as the fraction of power load which is provided by the PV power and similarly LF represents the fraction of PV production that has been consumed by the load. In order to put them in a mathematical way, figure 1 is presented below to show the load curve and generation curve with labels for the different energy part.

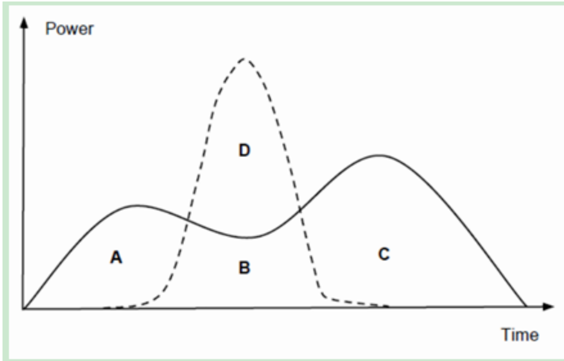

Figure 1: A demonstration of a load curve and PV generation curve with marks for energy which is for estimation of SF and LF. See equations 3.5 and 3.6 for definitions of SF and LF.

According to the correlation between the load curve and solar production curve displayed in figure 1, we get the mathematical expression for SF and LF:

$$\mathrm{SF} = \frac{\mathrm{B}}{\mathrm{A+B+C}} \quad (3.5)$$

$$\mathrm{LF} = \frac{\mathrm{B}}{\mathrm{B+D}} \quad (3.6)$$

For a net-zero energy building, whose electricity consumption is equal to the solar power production over a time scale of one year, SF and LF equal each other since the energy parts A+B+C and B+D have the same value.

3.4 Scenarios planning

Four scenarios were planned for simulation to investigate the aim of the project.

A. A single house with PV deployment and no EV load.
B. A single house with PV deployment and EV load
C. National electricity load with large scale PV deployment and no EV load
D. National electricity load with large scale PV and EV deployment

Scenarios A and B are planned to investigate the impact of EV introduction on the electricity consumption and PV self-consumption for a detached house or an apartment. Similar study has been conducted by Munkhammar (2012). However, Scenarios C and D are expanded to national level to further investigate the influence of large scale EV penetration on the electricity consumption and PV production. Different PV and EV penetration levels have been considered in Scenarios C and D according to the possible future situations.

3.4.1 Setup for EV at household level

Scenario A includes household electricity load and PV generation for a single household, but does not take EV charging into consideration. This is set as a reference scenario to compare with scenario B where EV charging is comprised into household load. As a consequence, it is possible to observe how much electricity consumption has been increased and what the impact on the PV self-consumption is when an EV is introduced and gets charged at home.

In order to quantify this impact of EV at household level, a standard setup developed by Grahn and Munkhammar is used for simulations in this project, which is presented in table 5.

Parameters	Notations
C^{Charge}	2.3 kW
SOC_{max}	35 kWh
SOC_{min}	21 kWh
C^{EV}	8.4 kW
$P_{EV}(t)$	20%
S(t)	0.8-1.2

Table 5. Standard setup for EV's variables

3.4.2 Setup for PV at household level

Net-zero energy means the production of PV power equals the total electricity consumption. This condition has been considered for scenarios A and B. For the system without EV load, the corresponding net-zero energy setup on a yearly basis is a PV area of 25 m^2. For the system with EV load, the corresponding net-zero energy setup for PV area is 34 m^2. However, simulations for scenarios A and B have been done under both PV area setups respectively. Taking the net-zero energy situations into account makes it comparable for the size of the PV models and possible to compare the self-consumption index SF and LF from more aspects, which could result in more accurate comparison and conclusion.

3.4.3 Setup for EV at National level

Royal Swedish Academy of Science (IVA) envisaged a vehicle fleet with 600,000 electric vehicles by 2020 (Swedish energy agency, 2009). Elforsk, the Swedish energy R&D organisation, estimated four possible scenarios for the number of electric vehicles in Sweden by 2030 based on different conditions of policies and technologies. Moreover, IEA made a blue map for the year 2050 that half of the light duty vehicle sold in the world would be plug-in electric vehicles.

Although the penetration level of electric vehicles in Sweden is low, the number of EV is promising to increase vastly in the near future. In this project we use Elforsk's three scenarios for the year 2030 in Sweden as input number of electric vehicles to investigate the impact of different amount of EVs. Therefore, Scenario D, which considers national electricity consumption, PV generation and EV energy consumption will be conducted under 4 different assumptions of EV penetrations, as shown in table6.

	EV numbers
Assumption 1	480,000
Assumption 2	650,000
Assumption 3	1780,000
Assumption 4	3270,000

Table 6 Different scale of EV fleet in Sweden assumed in this project

3.4.4 Setup for PV at National level

Widén's research indicated that an area of 370 km^2's building surface is suitable for PV installation in Sweden and there is no significant decrease in annual solar insolation if PV panels are optimally tilted with the latitude (Widén &Munkhammar, 2011). To simplify the model and setup for national PV energy generation, the same model as the one used at household simulation is applied to national level. That is, irradiance data from PV located in Uppsala and an efficiency of 13 are set for the national PV deployment. This model could generate annual electricity around 168 kWh per square meter on a plane tilted 45 degrees and facing south.

Net zero-energy setup for household level is not reasonable for national simulation considering about the potential for PV installation and the stability of grid. Three different scenarios formulated by EPIA for Europe in 2030 are referred for the setup of possible penetration in Sweden in a mid-term future. The potential PV area mentioned by Widén is also considered.

In terms of the simulations on national load without EV but with PV, four levels of PV penetration given in table 7 are investigated respectively. However, only PV penetration of 15% is choose to simulate household load with EV and PV.

PV penetration (%)	PV area (KM^2)
10	84
15	126
25	209
44	370

Table 7. Four different penetration levels of PV on national scale. 10% PV penetration means that 10% of annual electricity demand in Sweden is supplied by PV.

4. Results

4.1 Results of Household electricity consumption and photovoltaic production

In this section Scenario A and B has been simulated to quantify how the introduction of EV charging will affect the electricity consumption of a household and investigate whether it will help increase the coincidence between the energy consumption and PV generation, which is essential for PV self-consumption.

The input setups for EV and PV have been explained in section 3.4. The primary outputs of this simulation include household electricity consumption with home-charged EV considered or not, PV generations with different panel sizes, maximum power for consumption and generation, standard deviations for consumption and generation power on a yearly basis, as well as solar fraction and load fraction under different scenarios.

4.1.1 Household electricity consumption

The results regarding household electricity consumption is given in table 8. In terms of scenario A where EV charging is not taken into account, the annual electricity consumption for a household is 4.17 MWh. This has been increased by 36.5 % to 5.69 MWh when home-charged EV was included in scenario B. On the other hand, both maximum power for average daily consumption and that in a year have been increased by 71.4 % and 36.9 %. From these data, it could be concluded that EV represents a large amount of energy consumption if it's introduced to a household and it will increase the peak demand at household level to a great extent. This is also visible from figure 8 where average daily consumption and production of electricity is presented.

Since the simulation is conducted on a yearly basis, it is rational that there is different between daily average data and the actual daily or seasonal data. This is obvious if one compare the data for maximum power at daily average and that for maximum power in a year. Figure 9 is a four-day example of electricity consumption and generation in April. It is easy to find out the stochastic character of actual daily data from this figure. In order to figure out the relation between consumption and generation, it is critical to do the simulation on a yearly basis.

Standard deviation for household consumption power, as an index for measuring the variation between the actual values and the mean, is almost doubled when home-charged EV is introduced. This indicates that EV charging load has a much higher level of variation than that of normal household loads.

Scenarios	Annual consumption (MWh/year)	Max. Power for average daily consumption (kW)	Max. Power in a year (kW)	Std Power in a year (kW)
Without EV	4.17	0.70	4.52	0.37
With EV	5.69	1.20	6.25	0.73

Table 8. Primary results regarding household electricity consumption

4.4.2 Photovoltaic production

As mentioned before, two sizes of PV system have been equipped to the household respectively in order to build a net-zero energy environment which means PV production equals household electricity consumption. A household without EV is nearly in net-zero energy status with a 25 m^2 PV setup. If a home-charged EV is included, an area of 35 m^2 PV arrays is needed in order to match the extra consumption.

According to table 9, annual electricity production of PV rises 36 % from 4.21 MWh to 5.73 MWh as the panel area is increased from 25 m^2 to 34 m^2. Maximum power follows the same trend. These results are reasonable since production and power are proportional to PV areas. In addition, Standard deviation of power is also increased by 36% which indicate a larger variation with a larger PV area.
Similar to data for consumption, the actual electricity load varies significantly on both daily and seasonal basis, which is observable from the contrast between figure 8 and figure 9.

PV area (m^2)	Annual production (MWh/year)	Max. Power for average daily production (kW)	Max. Power in a year (kW)	Std Power in a year (kW)
25	4.21	1.70	4.56	0.87
34	5.73	2.30	6.20	1.18

Table 9. Primary results regarding PV production

4.4.3 PV self-consumption

Solar fraction of electricity load represents the fraction of consumption that is supplied by solar power, and load fraction of electricity production represents the fraction of solar generation that is consumed by load. These two indexes are used in this project for measuring the level of matching between consumption and PV generation, which is critical for improving self-consumption of PV. As stated in section 3.4.2, household electricity consumption with or without EV charging have been simulated under both sizes respectively.

Table 10 presents the results of self-consumption measures for four different scenarios. Scenario 1 (S1) and Scenario 2 (S2) have the same PV size of 25 m^2. EV charging is considered in S2 but not in S1. Additionally, Scenario 3 (S3) and Scenario 4 (S4) have the same PV size of 34 m^2, but EV charging is included in S4 not in S3.

Comparing S1 and S2, load fraction of solar production is improved by 10 percent from 31.31% to 34.39% while solar fraction of electricity load was decreased by 20 percent from 31.64% to 25.47% because of the introduction of an EV. It is similar situation when one compares S3 and S4. Load fraction is improved even more by 12 percent while solar fraction is reduced by 18 percent after the EV is introduced.

The result that load fraction of solar generation is increased after the introduction of EV means that EV charging does increase the amount of solar power consumed by local load and less solar power has to be injected to the grid. However, the reduction of solar fraction because of the EV introduction reveals the fact that EV charging has a lower matching level with PV generation than the normal household does.

Comparing S1 and S3, both of the two scenarios doesn't consider EV charging, but they are equipped with different PV sizes. It's obvious from table 10 that solar fraction is increased when the PV size is larger. This is because larger size increase the solar generation at a certain time, thus more load could be supplied by solar power.

S1 and S4 are both net-zero energy scenarios. It is interesting to notice that both solar fraction and load fraction have been decreased in S4 in comparison with S1. This implies that net-zero energy setup with EV charging has lower level of self-consumption than net-zero energy setup without EV charging does.

Another difference between with and without EV charging could be observed from the maximum net production and the maximum net load. EV charging decreases the former on a small scale but increases the later to a great extent. This implies that home-charged EV in the default setup has a larger negative impact on the grid than the positive impact it could make.

Scenarios	Solar fraction of electricity load (%)	Load fraction of solar production (%)	Max. net production (kW)	Max net load (kW)
S1. PV25-H	31.64	31.31	4.27	4.52
S2. PV25-H-EV	25.47	34.39	4.23	6.25
S3. PV34-H	34.36	24.99	5.91	4.52
S4. PV34-H-EV	28.22	28.00	5.87	6.25

Table 10. Results regarding self consumption

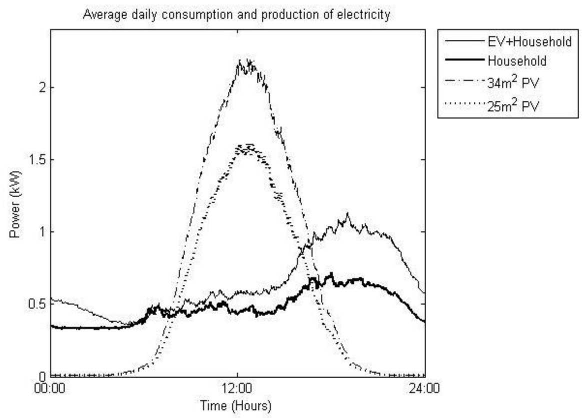

Figure 8:. Average daily electricity consumption and production on a yearly basis.

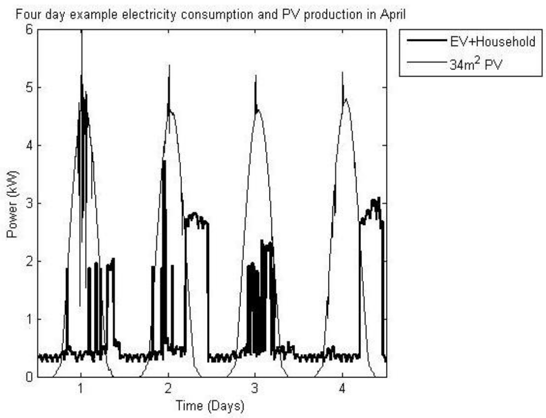

Figure 9: Four days example of electricity consumption and production in June

4.2 Results of National electricity consumption and photovoltaic production

This section presents the results regarding Scenario C and D, which aim to quantify the impact of EV charging on national electricity consumption in Sweden and examine its influence on the coincidence between energy consumption and large scale PV generation.

The setups for EV and PV penetration level were described in section 3.4. The main outputs of this simulation include national electricity consumption with EV charging considered or not, PV generations with four different penetration levels, solar fraction and load fraction. Maximum power for net consumption and net generation, standard deviations for net consumption are included as well. Net consumption here represents the electricity load subtracted by solar power. Similarly, net generation means solar power subtracted by load demand.

4.2.1. National electricity load without EV, and photovoltaic production

This simulation focuses on the relation between photovoltaic generation and electricity load without EV charging included. According to Nordspot pool (2013), annual electricity consumption in Sweden is currently around 141 TWh. PV panels with four different penetration levels generate different amount of solar energy corresponding to their capacity. Table 11 shows the results regarding this simulation and figure 10 depicts an average daily national consumption and PV generation with different penetration levels.

With an increasing level of PV deployment, solar fraction of electricity load is increased as more energy demand is provided by PV. It is interesting to notice that load fraction of solar power is 100 percent when the PV penetration is equal to or below 10%. This means that solar power is fully matched by domestic electricity consumption. In this situation, solar fraction will match with PV penetration. However, load fraction decreases with an increased PV penetration level as there are excess energy generated by PV and not consumed by domestic load.

Maximum net consumption doesn’t change with the increasing PV capacity. This is properly because the maximum electricity consumption happens when there is low or no PV generation. Inversely, the maximum net generation varies greatly with the alteration of PV capacity. Net PV generation means that there should be technical solutions for excess solar power which could cause insecurity for electricity grid.

Large scale of PV deployment results in drastic fluctuations on net consumption profile, which is evident in the comparison between figure 11 and figure 12. Furthermore, standard deviation for net consumption is directly proportional to installed PV capacity, which means that increasing PV application will make the load fluctuation more severe. This could be observed from figure 12. to figure 15.

PV penetration (%)	National electricity consumption (TWh/year)	PV generation (TWh/year)	SF (%)	LF (%)	Max. Net consumption (GW)	Max. Net generation (GW)	STD. for net consumption (GW)
10	141.32	14.17	10.02	100.00	26.52	2.29	4.63
15	141.32	21.25	14.64	97.40	26.52	9.80	5.69
25	141.32	35.24	20.35	81.62	26.52	24.65	8.16
44	141.32	62.39	26.27	59.51	26.52	53.44	13.45

Table 11. Results regarding the scenario of Natioanl load without EV but with PV

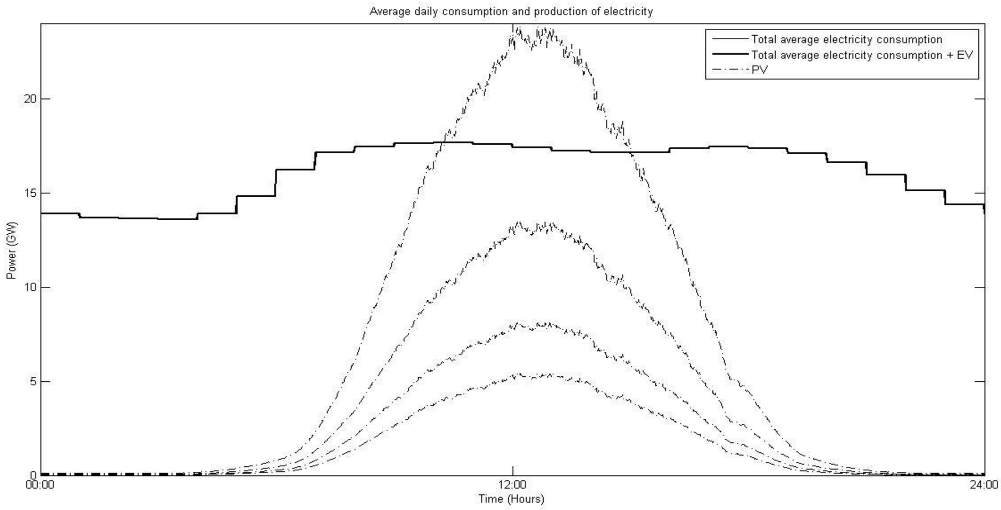

Figure 10: Average daily national consumption and PV generation with different penetration levels. Dotted curves from up and down represents the PV generation at a penetration level of 44%, 25%, 15% and 10% respectively.

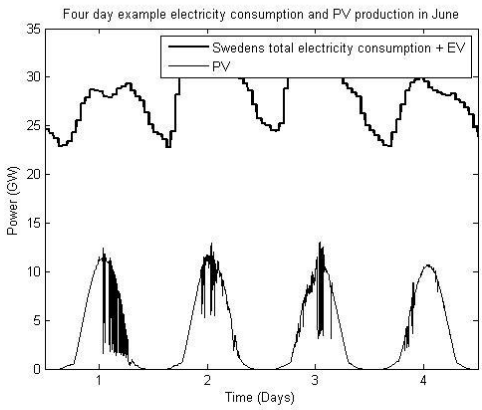

Figure 11. four-day example of electricity consumption and PV generation in June for scenario with 10 percent PV penetration.

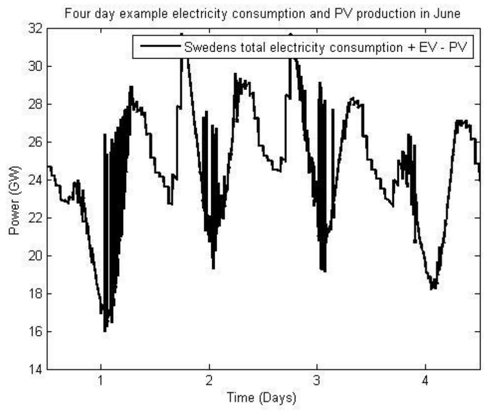

Figure 13. four-day example of net-electricity consumption in June for scenario with 15 percent PV penetration.

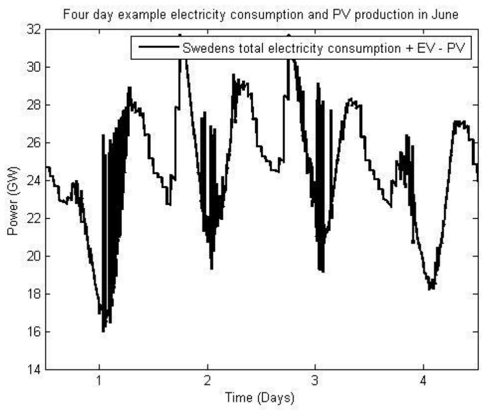

Figure 12. Four-day example of net-electricity consumption in June for scenario with 10 percent PV penetration.

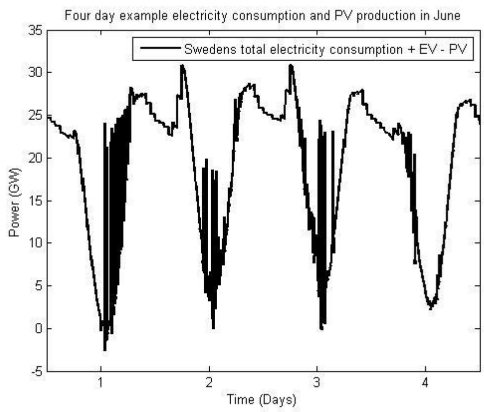

Figure 14. four-day example of net-electricity consumption in June for scenario with 25 percent PV penetration.

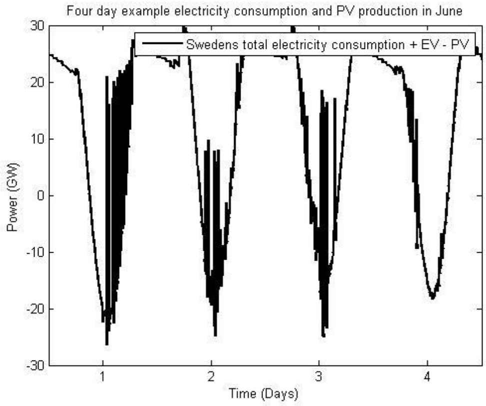

Figure 15. four-day example of net-electricity consumption in June for scenario with 44 percent PV penetration.

4.2.2. National electricity load with EV, and photovoltaic production

Since EV in Sweden is applied on a quite small scale, its influence on the national load profile is negligible at present. However it is interesting to see what the impact is when it's widely utilised in the future. PV penetration is set at 15% in order to compare the influence of different amount of EVs on PV self-consumption.

According to the data regarding PV generation given in the previous section, 10% penetration of solar power could be entirely consumed by domestic demand without excess production. In this case, Introduction of EV will not be helpful in improving PV self-consumption. However, 15% penetration of PV will generate a relatively small amount of excess power on the national scale. It is rational to choose this scenario as a basis to see whether the introduction of EV charging will help to improve PV self-consumption at certain level.

Table 12 gives prime results of national electricity consumption and PV self-consumption measures. In addition, figure 16. presents the daily average energy consumption and generation with a PV penetration at 15% and four different level of EV integration considered. When a number of 480,000 EVs are charged from the grid, national electricity consumption per year is increased by 0.6% and only 0.01 % increment is added to maximum net consumption power. In addition, maximum net generation of PV is decreased by 0.3%. This situation is similar to the one with 650,000 EVs. Based on the variation of maximum net consumption and maximum net generation caused by EV charging, it could be concluded that small scale EV penetration could slightly ease the pressure on the grid.

If the penetration level of EV is increased to a much larger scale to 1,780,000, energy consumption, maximum net consumption and net generation will show a greater variation. In the extreme scenario for EV integration into power system, 3, 270,000 units of EVs lead to an increase of 3.9% for national energy consumption which corresponds to 5.49 TWh/year. Meanwhile, maximum net consumption is increased by 4.3% and maximum net generation is decreased by 1.3%. This indicates that large scale EV charging will improve the peak demand and thus increase the pressure for the grid.

Load fraction of solar power grows with more EVs introduced to the grid because that more solar power could be matched by domestic energy consumption. Nevertheless, solar fraction of load is decreased by EV charging, which implies that the coincidence between EV charging and solar generation is relatively low. When there are 3,270,000 EVs integrated into the power system, load fraction is increased by 0.54% while solar fraction is reduced by 3.2 %. This fact manifests that large scales introduction of the default EV charging does not help to improve the matching level between energy consumption and solar power generation. In other words, EV charging at home without any strategic control will not help improve PV self-consumption but increase the pressure for the grid.

Increasing standard deviation of net consumption caused by EV implies that EV charging is a variety of load that is quite fluctuant, which is not beneficial for the stability of the power system.

EV numbers	National electricity consumption (TWh/year)	PV generation (TWh/year)	SF (%)	LF (%)	Max. Net consumption (GW)	Max. Net generation (GW)	STD. for net consumption (GW)
0	141.32	21.25	14.64	97.40	26.5170	9.80	5.69
480,000	142.13	21.25	14.57	97.48	26.5209	9.77	5.71
650,000	142.40	21.25	14.55	97.51	26.5224	9.75	5.71
1,780,000	144.31	21.25	14.39	97.70	26.946	9.67	5.75
3,270,000	146.81	21.25	14.17	97.93	27.65	9.57	5.81

Table 12: Results of solar generation and energy consumption including EV charging on national scale

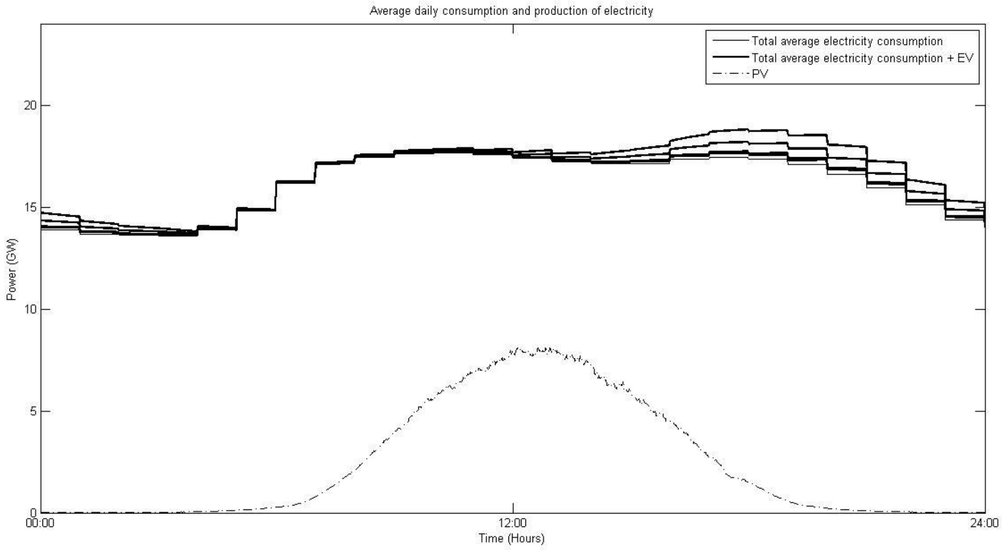

Figure 16. Daily average energy consumption and generation with a PV penetration at 15% and four different level of EV integration considered. Solid curves from up and down represents national consumption with a number of EV introduction at 3.72 million, 1.78 million , 0.68 million, 0.48 million and 0. The curves with EV number of 0.68 million and 0.48 million almost coincides.

5. Discussion

Increasing environmental pressures, such as peak oil and climate change, make it significantly important to develop the share of renewable energy in the local, regional or global energy system. Sweden has a vision of sustainable, resource-efficient and emission-free energy supply by 2050. Photovoltaics is one of the most promising renewable energy technologies with a decreasing price and relatively high efficiency to exploiting solar irradiation which is the most abundant energy resource in the world. On the other hand, electric vehicle as a technology existing more than one hundred years has gained increasing attention in the past decades because of its high potential to decrease green house emission (Ehsani et al., 2010).

Though Sweden is geographically located at high latitude, it has been proved that there is a great potential to deploy photovoltatics in Sweden (Widén &Munkhammar, 2011). Additionally, plug-in electric vehicle could be a decent option to fulfil the Swedish government‘s vision of a fossil fuel free transportation by 2030. Based on this premise, it is very likely that there will be a much larger scale penetration of photoltaics electricity generation and electric vehicle charging in the Swedish power system in a mid-term or long-term future. Therefore, it is interesting to investigate their interaction when both of them are integrated into the power system.

Photovoltaic power is often situated at the end-user side and light-duty passenger vehicle is one of the primary types for electric vehicles. Therefore, a household with introduction of a PV system and home-charged EV will be a preferable example to analysis the possible impact of integrating EV and PV into the energy system. There is previous research regarding this topic (Munkhammar et al, 2012). Furthermore, it is also meaningful to investigate the interaction between EV and PV on a much larger scale, for instance, whether plug-in EV will help improve the matching between PV electricity generation and national electricity consumption. This will help to estimate how much PV generation might be necessarily to export.

This project is designed to investigate the intersection between electricity use, EV charging and PV electricity production in the power system on both a household level and a national level. Research questions include how the application of PV and home-charged EV will influence the load profile and whether EV introduction will be beneficial to maximize PV self-consumption. Interpretations regarding the main results are presented in section 5.1 and 5.2.

5.1.Household energy use and photovoltaic production

A household with two inhabitants is according to the Widén-model net-zero for a 25m^2 setup. In that setup there is LF 31.31% and SF 31.64% If an electric vehicle is introduced then LF and SF is changed to 34.39% and 25.47% And in order to make the new situation net-zero energy, the PV-size has to be increased to 34m^2. This gives LF of 28% and SF of 28.22%.

This indicates that more electricity use will be supplied by local solar power but much more excess energy will be curtailed or injected into the grid which will increase the gird pressure.

In terms of EV charging at home, it will contribute a great amount of energy consumption to the household load, as much as 37% of the household electricity use, especially in the evening, night time and morning. The standard deviation of energy consumption is increased when EV is introduced. This is mainly due to the intermittency of EV charging.

PV generation mainly occurs during the daytime and has a peak at noon. However, home-charged EV is generally charged at evening and night time. This leads to a low coincidence and low matching between EV energy use and PV production. In other words, EV charging may increase the consumption of energy generated by local PV system at some extent and thus less excess energy from the PV system will be curtailed or injected into the power grid. On the other hand, EV charging requires larger electricity demand from the power grid rather than the local PV. Regarding the two net-zero energy scenarios, both of the self-consumption measures, solar fraction and load fraction decrease when EV is introduced, which means that net-zero energy building with EV has lower PV self-consumption than the one without has.

5.2. National energy consumption and photovoltaic production

In order to investigate how PV generation will change the national load profile, four scenarios of PV penetration, 10%, 15%, 25% and 44%, have been considered for simulations at the national level. According to the results, the standard deviation of the net load is directly proportional to PV capacity. This is due to the high intermittency and instability of PV power. Moreover, the maximum net generation is immensely improved when PV penetration grows larger, which indicates that a large scale of PV deployment could cause power system problems. Similar to the results of the household level, solar fraction is increased and load fraction is decreased when a larger scale of PV is introduced. It is interesting to notice that load fraction at 10% PV penetration is 100%, which means that solar power could be fully matched by the domestic load demand. However, there will be excess energy generation in other scenarios of PV penetration where load fraction is less than 100%. In terms of the national level, excess solar energy have to be stored with energy storage device, curtailed or sold to electricity market abroad. Another way to deal with excess generation is to increase the self-consumption of it.

15% PV penetration has been chosen as a reference setup to compare the influence of different EV numbers introduction. As shown in the results, an increasing number of EV charging in the power system will increase national electricity use at some extent. In the extreme scenario with 3,720,000 units of EV, national electricity consumption is increased by 3.9% which is much smaller than that of the household level, 37%. Besides, EV charging will increase the maximum net electricity consumption and reduce the maximum net electricity generation slightly. Due to the fluctuation and intermittency of EV charging, it also increases the standard deviation of the net load, which is not beneficial for the electricity grid. But since it is aggregated on a national level, the intermittency is much smaller than for an individual household.

After the introduction of EV charging in the power system, load fraction is increased while solar fraction is decreased. For example, load fraction is increased by 0.54% and solar fraction is reduced by 3.2 % with an EV number of 3,270,000. This reveals the fact that EV introduction consumes more solar power than the scenario without EV does, however it increases the electricity demand from the power grid rather than the local power system at a larger extent. This is due to the low level of correlation between EV charging and PV generation. Therefore, it could be concluded that the default EV charging without any strategic control will not help improve PV self-consumption but increase the pressure for the grid.

5.3. Limitation and future work

In order to simplify the model, it is assumed that EV is only charged at home and only one inhabitant at home uses it, which is not entirely realistic. If charging at workplace is considered in the model, the matching between EV charging and PV generation might be increased at some extent if the electric vehicle driving inhabitant works during the daytime and charges the car at peak generation time of PV. On the other hand, natural drive pattern is the basis of EV model in this project and smart charging is not taken into account. The result could be very different if smart charging is included since it could change the natural charging time with some incentives and thus improve the matching between EV charging and PV power production. Furthermore, vehicle to grid technology, where EV could be utilized as energy storage and provide energy to grid when needed, is not considered.

About the modelling of PV electricity generation, Irradiance data from the pyranometer at Uppsala is used to modelling the national PV generation. This might reduce the accuracy of the results. The PV generation profile on the national scale would be considerably smoother than the results from the simulation. Data from different measurement stations all over Sweden will be a better choice for modelling PV generation though it requires much more complex work.

All the limitations mentioned above could be interesting work for further research, especially smart charging and vehicle to grid technology which could have very different influence on the power grid.

6. Conclusion

Study on the interaction between the electricity use, electric vehicle electricity consumption and PV electricity generation has been conducted in this project. It is aimed to investigate the influence of PV and EV deployments on the electricity load profile and whether the introduction of EV charging will help improve the level of matching between electricity consumption and PV generation. The study has been done both for a single household and on a national scale.

The results from the simulations indicate that home-charged EV accounts for a large amount of energy consumption for a single household and it could increase national energy consumption to some extent if it is introduced on a large scale into the power system. In addition, Home-charged EV without strategic control does not improve the match between the electricity consumption and PV electricity generation either for a single household or on a national scale. In other words, it does not enhance the self-consumption of PV. The influence on PV self-consumption from EV charging with a consideration in smart control and V2G technology will be interesting for future work.

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