CHALMERS
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Local DC Nanogrid Up-Scaling to Block Level Interaction

Master's thesis in Electric Power Engineering

ARYA SASEENDRAN NAIR

BLESSING KABASA

Department of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Supervisor: Patrik Ollas, Department of Electric Power Engineering
Examiner: Torbjörn Thiringer, Department of Electric Power Engineering

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Department of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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BLESSING KABASA
Department of Electric Power Engineering
Chalmers University of Technology

Abstract

Lately, the interest in the use of a DC microgrid distribution system has increased because of its ability to easily integrate with different renewable sources, energy storage systems and electric vehicles. The main aim of the thesis was to analyse whether the power-sharing between different buildings (nanogrids) in a microgrid system is worthwhile or not. Different DC nanogrids were modelled first separately and then interconnected to form a microgrid with a view to compare the two scenarios. Both scenarios were equipped with gateways to the utility grid. Five different nanogrids were evaluated, and each case contained different photovoltaic panels, batteries and DC load profiles. The simulation was done in Matlab using practically obtained one-year PV and load data. Also, a study on the possibility of utilising blockchain energy management in microgrids is presented.

The simulation results show that the interconnection of nanogrids to form a microgrid improves the overall self-consumption of the system by 20.9 percentage points whilst the self-sufficiency is also improved by 7.1 percentage points. Furthermore, amongst other small notable improvements, it is also beneficial financially to have peer to peer energy transactions within a microgrid.

Keywords: DC nanogrid, DC Microgrid, DC voltage, solar PV, self-sufficiency, self-consumption, blockchain.

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Arya Saseendran Nair and Blesssing Kabasa
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Contents

List of abbreviations

Ac	Annual cost
DER	Distributed energy resources
DOD	Depth of discharge
DSM	Demand side management
EV	Electric vehicle
FYy	First year yield
i	Years
Ii	Initial investment
Ir	Interest rate
kW	Kilo watt
kWh	Kilo watt hour
kWp	Kilo watt peaks
LCOE	Levelized cost of electricity
n	Lifetime of the system
RTPV	Roof Top Photo Voltaic
Rv	Residual value
SC	Self-consumption
SDr	System degradation rate
SOC	State of charge
SS	Self-sufficency
SSM	supply side management
V2G	Vehicle to grid
V2H	Vehicle to home
ZEB	Zero energy building

1 Introduction

1.1 Background

The requirement of energy in the world is becoming higher day by day and to compensate for that, new energy resources are needed. However, taking advantage of fossil fuels is not everlasting. The resources such as coal, petroleum, natural gas are limited and the burning of fossil fuels results in CO2 emission which causes climate change from global warming.

The aim of almost all countries is to achieve an energy sustainable future. Generation of electricity using non-renewable sources of energy produces tons of carbon dioxide which lead to global warming. 40% of the worldwide energy is consumed by buildings and they are responsible for 30-40% of carbon emissions. So, if any changes in the building operating mode can help to minimise the building's carbon footprint, it is very valuable. The concept of zero energy building (ZEBs) is that the building will be able to produce the amount of energy they require. ZEBs are buildings that work in collaboration with the utility grid to avoid putting extra stress on the power infrastructure. The ZEB´s aim is to achieve sustainable development by incorporating renewable sources for the production of electricity. As a result, less greenhouse gases are emitted to the atmosphere by a ZEB as compared to a similar none-ZEB [1].

Switching to a sustainable future is a complicated process and it requires three main technological changes: energy production should be more efficient, fossil fuels have to be replaced and there should be the provision to save on the consumer end. The research and development in the field of power systems facilitate the use of microgrids to support the sustainable development of a country. DC microgrids gain much focus nowadays due to lower losses and also since there is no reactive power. AC systems have been dominant in power system for more than a century but things have changed, above all, the development of power electronics and also due to the recent interest in renewable energy sources. Many studies have indicated that DC microgrids are more suitable for the distribution systems in a building than the AC distribution systems. The main advantages of the DC microgrids are high efficiency [2].

Some studies have proposed the use of DC for residential and commercial loads claiming that the majority of the loads today are actually using DC voltage. Lighting, electronics devices, washing machines etc are some examples of loads that can favourably be fed by DC. A few papers have proposed certain standard values for DC voltage buses like 380V and 48V. Electronics devices could easily be supplied by 48V or 28V DC instead of AC [3].

1.2 Aim and Scope

The aim of the thesis is to carry out a feasibility study on the implementation and up-scaling of DC nanogrids to form a microgrid. Much focus is on simulating the interaction of multiple DC nanogrids and monitoring the power flow between the nanogrids. One of the main objectives of this thesis is to optimise usage of PV energy, reduce energy taken from the AC grid and maintaining DC bus voltage under the variation of loads and sources.

The scope of the thesis is to upscale different DC nanogrids into a DC microgrid level. Different DC nanogrids were modelled first separately (scenario 1) and then interconnected to form a microgrid with a view to compare the two systems (scenario 2). Both systems were equipped with gateways to the utility grid. Five different nanogrids were evaluated, and each case contained different photovoltaic panels, batteries and DC load profiles. The simulation was done in Matlab using practically obtained one-year PV and load data. Also, a study on the possibility of utilising blockchain energy management in microgrids is presented.

1.3 Outline of the thesis

- **Chapter 1 Introduction** - Covers the background information regarding zero energy buildings and importance of DC microgrid. Also, the aim and scope of the thesis work are described.
- **Chapter 2 Theory** - Describes the theory behind the nanogrid, micro grid, PV selection, interaction of electric vehicles with nanogrids as well as the utility grid. Also, the theory covers the Swedish energy market in detail.
- **Chapter 3 Case study** - Chapter includes the different nanogrid case studies considered. The data and values used for this modelling of the nanogrid are explained.
- **Chapter 4 Blockchain & Microgrid**- Functional principles and advantages of blockchain technology are described. Also, the application of blockchain in microgrid system is explained in this chapter. Limitation of the blockchain application in the microgrid is also explained.
- **Chapter 5 Results** - Results from the MATLAB simulation model is presented in this chapter.
- **Chapter 6 Discussion** - Discussion of the result is done in this section. Also, the ethical and sustainable aspect of this work is discussed in this chapter.
- **Chapter 7 Conclusion** - Covers the main findings of this thesis and concludes the answers to the core questions. Finally, future work related to this project work is mentioned.

2

Theory

2.1 Definitions

2.1.1 Nanogrid

A nanogrid can be defined as the local power distribution system for a single house or a small building. It can connect or disconnect from the utility grid through a gateway. A nanogrid consist of a local power production such as solar PV panels, wind turbine etc., which will be the primary source to power the loads in that house. Another common element in a nanogrid is an energy storage system such as a battery. It helps to improve the maximum utilisation of the PV power produced in a nanogrid. The energy stored in the battery can be used to provide power to the load in the absence of solar power production. The thesis study includes 5 nanogrids. 4 nanogrids are residential houses and the other nanogrid is an office building. There is no interconnection between the houses and the power-sharing is between the nanogrid and the utility grid. Figure 2.1 shows the basic block diagram of a DC nanogrid.

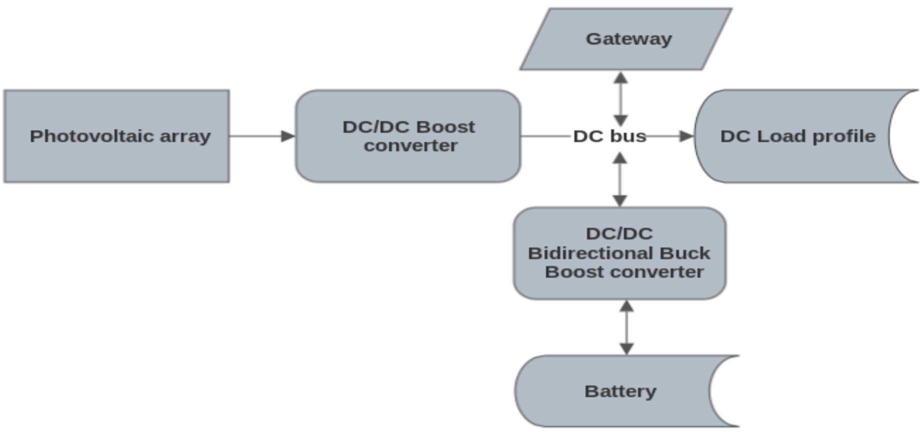

Figure 2.1: DC nanogrid block diagram

2.1.1.1 Structure of a nanogrid

The main components in a nanogrid are: a renewable energy source or several sources, an energy storage system, a power electronic converter system, gateway and the load [4].

- **Renewable electricity production** - The main sources of renewable energy for a nanogrid are solar and wind. So, the power production sources in a nanogrid are solar PV panels and small-scale wind turbines. In this thesis, only solar PV panels are considered. The household Roof Top Photo Voltaic (RTPV) systems have gained interest since they decrease grid power consumption [5].
- **Energy storage** - Energy storage technologies include electrochemical devices that convert electricity into chemical energy and then reverse the process for the provision of power (i.e. batteries). There are several types of batteries for microgrid applications including lead-acid, lithium-ion, etc. In nanogrid architectures, an energy storage such as a battery is not a compulsory component. However, adding an energy storage gives stability to the system. The battery storage system provides uninterrupted power supply to the loads. The type of energy storage considered for the thesis work is a Li-Ion battery. There are several other types of energy storage systems other than batteries that can be used.
- **Power electronic converters** - The power electronics converters in a nanogrid include a step-up DC-DC converter, a step-down DC-DC converter, bidirectional DC-DC converter and a bidirectional AC-DC converter. The DC-DC boost converter is used to step up the voltage produced from the solar PV to bus voltage level. Where step down DC-DC converter is used to step down the bus voltage to a load level. This conversion is performed by a buck converter. The efficiency of a load DC-DC converter is normally greater than 80% and well designed ones can have greater than 90% efficiency [4]. The bidirectional AC-DC converter is used for the gateway.
- **A Gateway** - The bidirectional power connection between other nanogrids, microgrids or the national grid is a gateway. The gateway also has the ability to disconnect the nanogrid from the main grid so that it can work in islanded mode.
- **Loads** - The loads are the electrical household appliances such as oven, television, lighting etc. The produced power is supplied to the loads.
- **Nanogrid control** - It is considered as the brain of the system. If the control is implemented correctly it will increase the efficiency of the nanogrid system. By implementing a nanogrid control it gives the ability to coordinate multiple sources. Also, the power production and consumption can be optimised. The main two categories to control in a nanogrid are supply side management (SSM) and demand side management (DSM) [4].

2.1.2 Microgrid

A microgrid can be defined as the local power distribution system for a group of buildings. A nanogrid is a building block of a microgrid so a network of multiple nanogrid forms a microgrid. In this study the microgrid is defined with 4 residential nanogrids and an office nanogrid. In this microgrid system a peer to peer power-sharing is implemented. So, if there is an excess in one nanogrid they can sell the power to neighbouring nanogrid or to the utility grid. Figure 3.16 shows the defined

DC microgrid system of this thesis work.

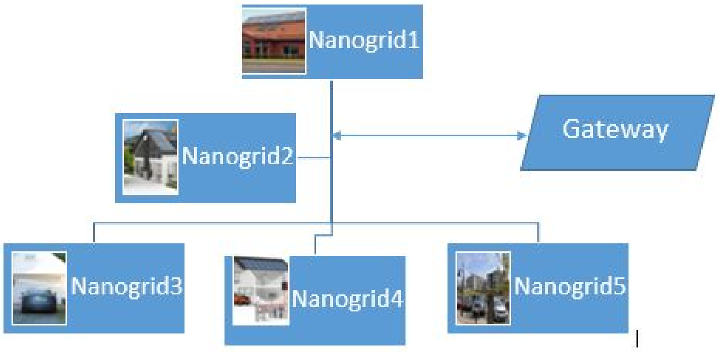

Figure 2.2: DC microgrid block diagram

2.1.2.1 Advantages of microgrids

The benefits of microgrid to the environment, to utility operators, and to customers are described below.

- **Renewable deployment & CO2 footprint reduction** - Environmental policies in many countries are demanding higher rates of renewable deployment for carbon footprint reduction. Microgrids offer the opportunity to deploy more zero-emission electricity sources, thereby reducing greenhouse gas emissions. Microgrids consisting of flexible loads, storage, and advanced control systems are able to integrate larger amounts of intermittent renewables into the system at the local level. They are able to coordinate between different distributed energy resources (DER) and balance power demand and supply locally and efficiently.
- **Flexibility and increased PV self consumption** - Microgrids can continuously power individual buildings, neighbourhoods, or entire cities, even if the main utility grid suffers an outage. The concept of a microgrid functioning independently from the utility grid is known as islanding [6]. The microgrid can provide uninterrupted power supply to their customers during unexpected power outages, such as natural disasters and faults in the utility grid. This application is very important for critical loads, such as hospitals etc. Less essential loads can be switched off to increase the withstand time depending on the availability of the primary source of energy. Reduction of utility grid interaction will result in improving the self consumption. Governments that observed the importance of islanding are offering subsidies for microgrids.
- **Electricity bill reduction** - Microgrids can help to reduce and control the electricity demand and mitigate grid congestion. It helps to lower the electricity prices and reduce the peak power requirements. In remote areas where electricity is still not available, a microgrid can help to avoid costly investments for new substations, transmission lines or other infrastructure. Microgrids, with advanced control technologies, can generate electricity mainly from

renewables only adding a small cost compared to the conventional utility grid. Additionally, as renewables do not require fuel cost, the electricity tariff is not influenced by the high fuel cost. The price can be lower because there are no transmission losses and sophisticated transmission equipment requirements since the grid interaction will be reduced. So, in remote areas microgrids can reduce electricity bills for customers.

2.1.3 Self consumption

Self consumption can be defined as the percentage of the total generated PV that is used internally. It can be calculated as

$$SC = \frac{PV\ consumed\ internally}{Total\ PV\ generated} \tag{2.1}$$

2.1.4 Self sufficiency

Self sufficiency can be determined as the percentage of the total load that is supplied by the locally generated PV energy. It can be calculated as

$$SS = \frac{PV\ consumed\ internally}{Total\ electricity\ demand} \tag{2.2}$$

2.2 Sizing of solar PV panels

Solar PV panels are becoming more affordable and efficient. This section focuses on how to select the size of solar PV to avoid an unexpected purchasing decision. The main aim of a solar PV system is to offset all or some of the electricity needs [7]. The size of a solar PV panel is calculated as

$$PVsize(kWp) = Daily\ kWh * Insolation\ hours * 1.25 \tag{2.3}$$

where daily kWh is the daily electricity usage and solar insolation is the number of hours the solar panels are exposed to direct sunlight in a day. By inputting the latitude and longitude of the location the insolation data for a year can be collected. From [9], the minimum hours of sunlight received in Borås is 6.43hrs. To this calculation, the standard energy losses of solar PV systems and an oversizing factor of 1.25 should also be considered when estimating the size of the PV system [8].

- **Determination of Daily kWh** - The first step is to calculate the average monthly electricity usage from the past electricity bills. The monthly average electricity usage is calculated because the load demand varies in summer and winter. The daily kWh is then subsequently calculated from the monthly averages.

- **Determination of the solar insolation hours** - Solar power generation is based on the incident sunlight on PV panels. Therefore it is necessary to know how many hours of direct sunlight the panels will be exposed to in a day. Specific insolation data for individual days of a year can be found in the NASA's Atmosphere-Ocean model. In this study, 6.43hrs is the insolation data according to the insolation table. This value is obtained by entering the latitude and longitude data for Borås [9] [10].

2.3 Pay back period calculation

It is important to calculate the pay back period of a DC microgrid system in order to know the financial aspect of the project. It is critical to determine the combined costs and annual benefits to calculate the solar PV panel payback period.
A levelized cost is defined as the net cost to install a renewable energy system divided by its expected life-time energy output. The levelized cost of electricity (LCOE) is calculated as

$$LCOE = \frac{Ii + nAc - Rv}{\frac{\sum_{i=1}^{i=n} FYy(1-SDr)^{i}-1}{(1+Ir)^{i}}} \tag{2.4}$$

where, Ii is the initial investment, Ac is the annual cost, Rv is the Residual value, FYy is the First year yield, SDr is the System degradation rate, Ir is the Interest rate, i is years and n is the lifetime of the system.

The LCOE values rely upon the assumptions that are made while designing the system. At present, the interest rates are very low in Sweden, and for private persons, the rate is 5 % on savings accounts in almost all Swedish banks. The total cost of installing a solar PV panel is dependent on the size of the system and other equipment included in the system. The tax breaks and a subsidy can reduce the cost of a solar PV installation. Also, the average monthly electricity consumption is an indicator of both the size of the system needed and the amount of electricity that can be saved each month with the solar panel. If the electricity bill is higher, then the estimated payback period will be shorter. Because soon after the installation of solar panels, the electricity bill can be reduced or eliminated. Some factors such as weather variation may impact the amount of electricity estimated to produce. Some countries provide additional incentives for renewable sources of power production. This should also be considered when calculating the payback period.

Some of the factors that might move up the LCOE of a project are inadequate maintenance, batteries and interest paid for the financial loans to the bank etc. The system performance can degenerate over time which results in reducing the total kWh output of batteries and resulting in replacement. So, lack of maintenance can negatively affect the LCOE.

Some specific tax laws that affect self consumption of small private PV system are shown in the Table 2.1 [11]. Table 2.2 [11] shows the subsides for solar PV that are provided by the Swedish government and Table 2.3 shows the assumptions and values that are used for calculations.

Table 2.1: Summary of self consumption rules for small private PV systems in 2016

PV self consumption	1	Right to self-consume	Yes
	2	Revenues from self-consumed PV	Savings on the electricity bill
	3	Charges to finance Transmission & Distribution grids	None
Excess PV electricity	4	Revenues from excess PV electricity injected into the grid	Various offers from utilities + 0.6 SEK/kWh + Green certificates
Other characteristics	5	Regulatory scheme duration	Subject to annual revision
	6	Third party ownership accepted	Yes
	7	Grid codes and/or additional taxes/fees impacting the revenues of the prosumer	Grid codes requirements
	8	Regulations on enablers of self consumption (storage, DSM...)	None
	9	PV system size limitations	Below 100 Amp. And maximum 30 MWh/year for the tax credit
	10	Electricity system limitations	None
	11	Additional features	Feed in tariffs from the grid owner

Table 2.2: Cost breakdown for a grid connected roof mounted system

Cost category	**Average cost for residential PV system (SEK/Wp)**	**Average cost for commercial PV system (SEK/Wp)**
Module	6.26	5.98
Converter	1.78	0.94
Mounting material	1.17	1.28
Other electronics (cables, etc.)	0.54	0.74
Planning work	0	0.21
Installation work	2.43	1.52
Shipping and travel expenses to customer	0.33	0.26
Permits and commissioning (i.e. cost for electrician, etc.)	0.55	0.53
Other costs	0.16	0.07
Profit margin	2.34	1.17
Total	19.45	12.70

Table 2.3: Assumptions made

Sl.No	**Assumptions**	**Value**	**Comment**
1	PV panel life span	30 years	-
2	Solar PV subsidy	30%	Subsidy covered 30% of the installation costs of PV systems, including both material and labour costs up to a maximum cost of 1.2 million SEK as from the year 2018 .
3	Life span of inverter	15 years	-
4	Battery cost	209 USD/kWh	The price considered is for the year 2018 [12].
5	Life cycle of battery	3000 cycles	Lifetime at 80% Depth of discharge [12]
6	Battery subsidy	60%	Costs including the installation of battery, cabling,control systems, smart energy hubs and work time. The subsidy is only granted to private persons. Maximum limit is 50000 SEK [13].
7	PV tax return	0.6 SEK/kWh	-
8	Selling price of electricity	0.5 SEK/kWh	-
9	Buying price of electricity	1.4 SEK/kWh	-
10	Income for selling to grid	0.05 SEK/kWh	Income for selling excess PV generated electricity to utility grid "nätnytta"
11	Electrical certificate	0.147 SEK/kWh	Payed to up to a maximum of 15 years
12	Guarantees of origin	0.005 SEK/kWh	-

2.4 Regulatory and Technical challenges

Even though there are lot of advantages for microgrids, the rate of implementation has remained lower than one would anticipate. This is mainly because of the uncertainties in the regulatory environment. Currently, no technical or legal definition of a microgrid can be found in the Swedish energy regulations. Some of the available regulations related to power-sharing, energy storage and technical challenges are listed below.

- **Sharing of energy** - Based on the current Swedish "nätkoncession" law, it is not allowed to share power between two properties. So, it is not possible to sell the excess power generated from solar PV panel to neighbouring houses.
- **Energy storage** - As per the regulation related to energy storage at present, it is not allowed for an energy storage to be taken up in the revenue frame. However, there is no prohibition to buy and use for self-purpose. Excess power generated from PV can be stored in an energy storage and this stored energy is not allowed to be sold to other houses.
- **Integration of Electric cars** - One obstacle to integration of EV to nanogrid is that the instruments available today to promote a charging infrastructure does not reward equipment prepared for load control. This can constitute an obstacle to investing in equipment that is slightly more expensive for the customer, but that could reduce the overall social costs of the installation.
- **Technical challenge** - Some of the technical problem associated with microgrids operation are interconnection schemes between microgrids and the main grid, frequency control during islanded operation [14] and voltage-control schemes within a microgrid [15] [16] [17].

2.5 DC voltage in household building instead of AC voltage

Photovoltaic modules, batteries (the most used energy storage system) and the V2G technology supply a typical nanogrid with DC. The use of batteries as an energy storage system is increasingly becoming popular because of the higher energy storage capabilities and the drop in prices due to technological advancement in that area [18]. To increase operational efficiency by minimising the losses realised during energy conversion from DC to AC and back to DC again, DC nanogrids are favoured. The conversion of AC to DC is less efficient as relatively huge losses are incurred as compared to the cheaper and efficient DC-DC conversions. This therefore entails that, had it not been for the limited number of home appliances designed to use DC, designers would now prefer the use of DC voltage in households [19].

Proposals for the use of DC in households is gaining momentum because the majority of the household appliances are natively DC even though they are currently designed to be powered by AC [4]. Some of these appliances are LED lighting, most of the small motors and almost all electronics like televisions, radios, laptops and so on. The best household electrical design should be such that electrical losses are minimised both at transmission and conversion level. For a DC nanogrid, there is the need to most economically utilise the locally generated DC power.

The proposed voltage level is 380 V DC to power high voltage loads, electric car charging and other major home appliances. The other proposed voltage level is 48V DC for all the tabletop appliances like computers and other various entertainment systems and the LED lighting. The 380V DC is selected to match the AC standard intermediate consumer electronics voltage [18].

2.6 Electric vehicles interaction with nanogrid and utility grid

With the ever-increasing drive to reduce carbon emissions from oil and promoting sustainable solutions, proposals have been made to replace fossil fuel based vehicles (internal combustion engines) with electric vehicles. Various measures have been taken and an increase in the manufacture of electric vehicles has been noted [26]. Power system operators have embarked on extensive research to determine the impact of the electric vehicles on the grid. Likewise, the grid is undergoing its fair share of changes in line with the environmental issues regarding clean energy. These changes include the transition from a centrally controlled grid to a distributed grid characterised with renewable nanogrids and microgrids.

Electric vehicles have lately seized to be viewed as static loads but as controllable loads. Since an electric vehicle is equipped with a battery, the electric vehicle can also act as a distributed generator and compensate for the transient nature of renewable sources like solar and wind. Furthermore, the EV can also supply energy to the grid during peak loading times [20]. The electric vehicle can smoothen the domestic electricity demand of a nanogrid and in the process, increase its reliability and power stability [21]. A vehicle can support a grid through the use of charge rate modulation with unidirectional power flow or through the use of a bidirectional power flow charger as shown in Figure 2.3 [22, 23]. Focusing on nanogrids, much research is being done on the interaction between a nanogrid and an electric vehicle and this is often referred to as a vehicle to home interaction (V2H). When the nanogrid is upscaled to a microgrid level and also at macrogrid (utility grid) level, it becomes a vehicle to grid interaction (V2G) [24].

2.6.1 Vehicle-to-Home Framework

From a simple point of view, a V2H framework consists of a nanogrid and a single electric vehicle. The electric vehicle is equipped with a bidirectional DC charging system. The electric vehicle is therefore charged by the nanogrid during off-peak hours and in return, the electric vehicle can help the local energy storage system to smooth the household daily load profile during peak hours. V2H can therefore greatly improve the development of nanogrids as it is not so difficult to install the

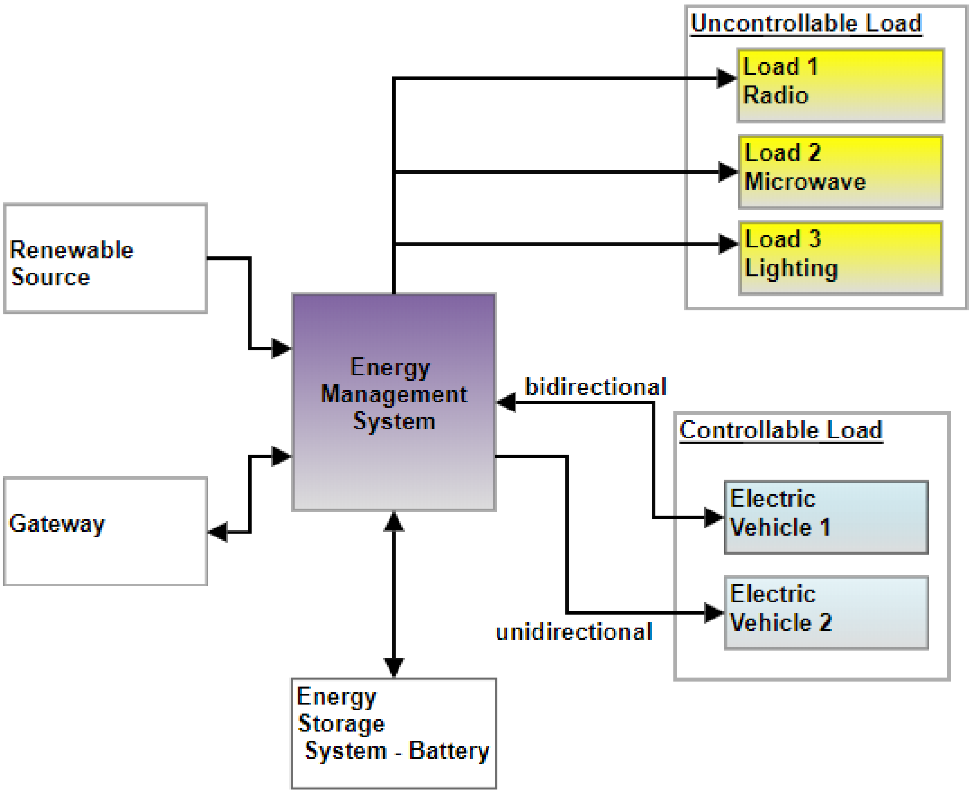

Figure 2.3: Vehicle-to-Grid concept in nanogrids

bidirectional charger through a controlling algorithm to ensure that the vehicle is left with enough energy for driving.

The V2H technology is already gaining momentum as other car manufacturers are also taking part in the research process. A good example is the Nissan's Leaf-to-Home where Nissan leaf batteries are used to support nanogrids through the electric vehicle's power station unit [25]. However, in this paper, the focus is on the use of an onboard bidirectional charger that makes a vehicle a controllable load and a distributed generator that compensates for active power mismatch as shown in Figure 2.3. On average, private vehicles are parked for 93-96% of their lifetime [26]. Of the said percentage, most of the vehicles are parked at home by 7 pm to 7 am, hence the vehicle can be connected to the nanogrid for an average of up to 11 – 12 hours per day [27]. The electric vehicle can, therefore, be used to provide energy to priority loads during outages, compensate for the intermittency of solar and other emergencies. However, since the electric vehicle is not always parked at home and should also then have sufficient charge for driving each morning, V2H is not intended for real-time energy compensation but an auxiliary energy storage system.

2.6.2 Vehicle-to-Grid

Vehicle to grid technology focuses on the provision of energy and subsequent addition of regulation or spinning reserve to a grid by electric vehicles. In as much as the electric vehicle battery's lifetime is reduced by the increase in charging and discharging whilst parked, the owner can make a net profit from selling power to the grid. On the other hand, the utilities can also benefit from V2G as system flexibility is increased since it can push extra power to the connected electric vehicles and take it back when there is a shortage.

Unlike the simple V2H, V2G is more complex as it involves tariff modelling since any vehicle within the system can be connected and be used to stabilise the grid. In as much as having more electric vehicles being connected to a microgrid brings with it utility grid flexibility, it becomes difficult to control. Since a microgrid can also incorporate other sources of renewable energy like wind which is AC based, it should be noted that the bidirectional charger's DC link capacitor can inherently provide reactive power to support the AC grid. Hence, several connected electric vehicles can be used to support a commercial or an industrial nanogrid. The control algorithm should incorporate the arrival and expected departure time of the vehicle, the state of charge at arrival, the energy consumption of the nanogrid or microgrid and the forecasted day-ahead electricity prices from the utility [22]. This is to ensure that the owner of the vehicle does not run out of travelling energy because of V2G.

2.7 Up-Scaling to block level interaction

A nanogrid is a building block of a future state called the Local Power Distribution where electricity generation and distribution should be managed from the bottom up [28]. The nanogrid is the smallest block with local generation, load, capacity monitoring and pricing. For reliability and stability enhancement, individual nanogrids can be interconnected to form a microgrid. The nanogrid block can therefore be up-scaled to a microgrid and have microgrid controllers that will interface with the respective nanogrids controllers as the gateway to the utility grid will be moved from the nanogrid to the microgrid level.

Within the microgrid level, the power transfers and price negotiations between nanogrids are generally at a peer to peer basis [18]. The controlling techniques become more complicated from the nanogrid level to the microgrid level and eventually at the utility level. There is much need for further research on the upscaling of a single nanogrid to a single microgrid consisting of a number of interconnected nanogrids. The aim would be to minimise the net power consumed from the utility grid and instead, promote peer to peer power purchases that are beneficial to both the seller and the buyer.

3

Case study

3.1 Scenario 1: DC nanogrids with no interconnections

The first scenario will focus on the performance of nanogrids operating in grid connected mode. Currently in Sweden, the regulations do not permit nanogrids to share power amongst themselves hence if a nanogrid has a power deficit it can only import power from the utility grid and if the nanogrid has excess power, it can only sell it to the utility grid. This setup is analysed as scenario 1 in this study.

Table 3.1: Parameters of all cases

Case study	**Annual energy usage [kWh]**	**Daily energy usage [kWh]**	**PV size [kWp]**	**Battery size [kWh]**	**No.of EVs**
DC nanogrid 1	21610	59	11.50	7.2	1
DC nanogrid 2	14170	39	7.5	No battery	1
DC nanogrid 3	9455	26	No PV	No battery	1
DC nanogrid 4	16690	46	9	13.5	0
DC nanogrid 5	64970	178	35	No battery	3

3.1.1 DC nanogrid-1

DC nanogrid-1 is modelled with a PV array, battery storage and an electric vehicle. Figure 3.1 shows the schematic diagram of the DC nanogrid-1 and Figure 3.2 show the Matlab/Simulink/SimscapePowersystem model of the system. Details about the parameters of the nanogrid subsystem are given in Table 3.1 and the load profile of DC nanogrid-1 is shown in Figure 3.3.

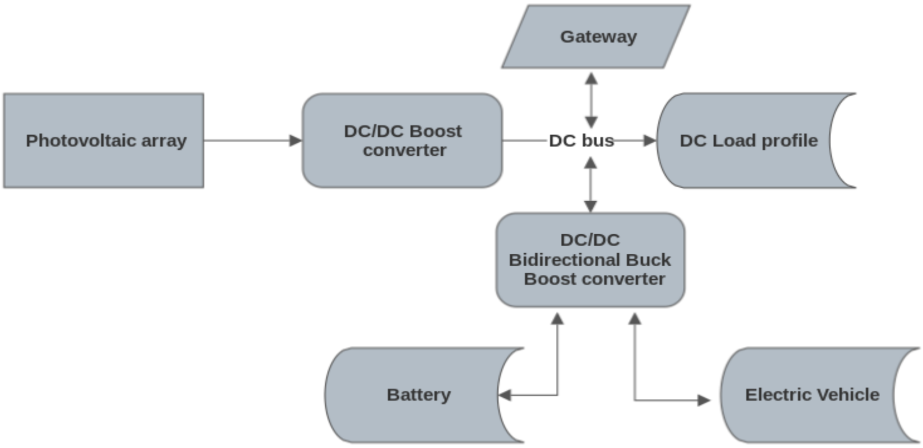

Figure 3.1: Schematic diagram of DC nanogrid-1

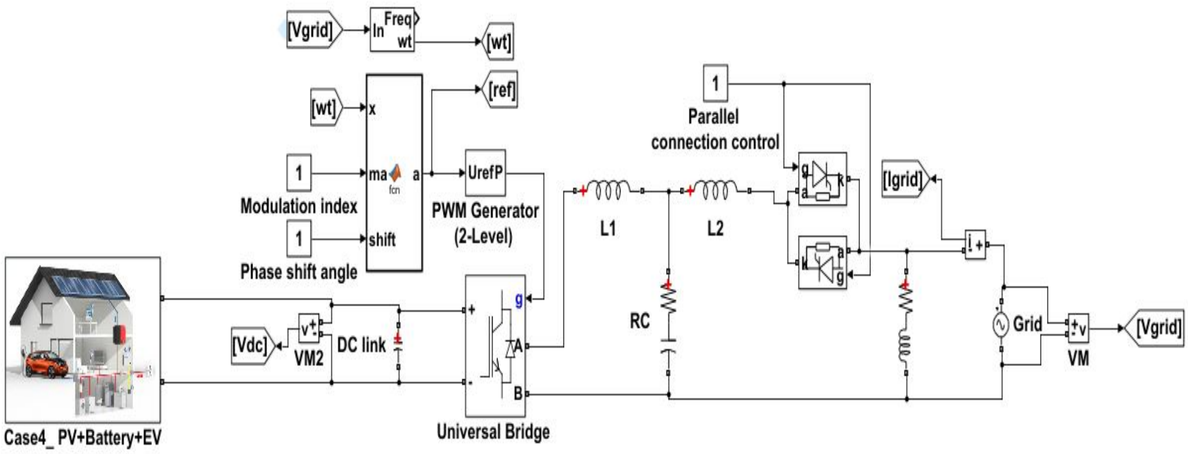

Figure 3.2: Model of grid connected DC nanogrid-1

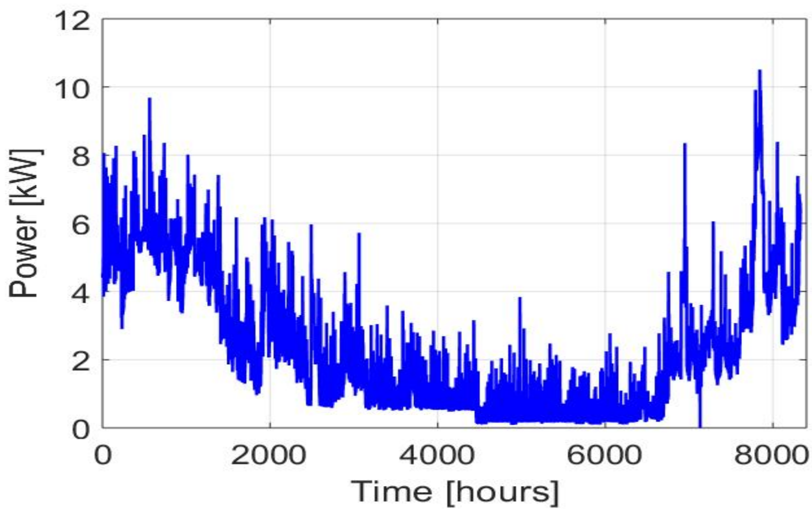

Figure 3.3: Load profile for Nanogrid 1

3.1.2 DC nanogrid-2

DC nanogrid-2 is modelled with a PV array and an electric vehicle. Figure 3.4 shows the schematic diagram of the DC nanogrid-2 and Figure 3.6 shows the model of the grid connected DC nanogrid-2. Details about the parameters of the nanogrid subsystem are given in Table 3.1 and the load profile of DC nanogrid-2 is shown in Figure 3.5.

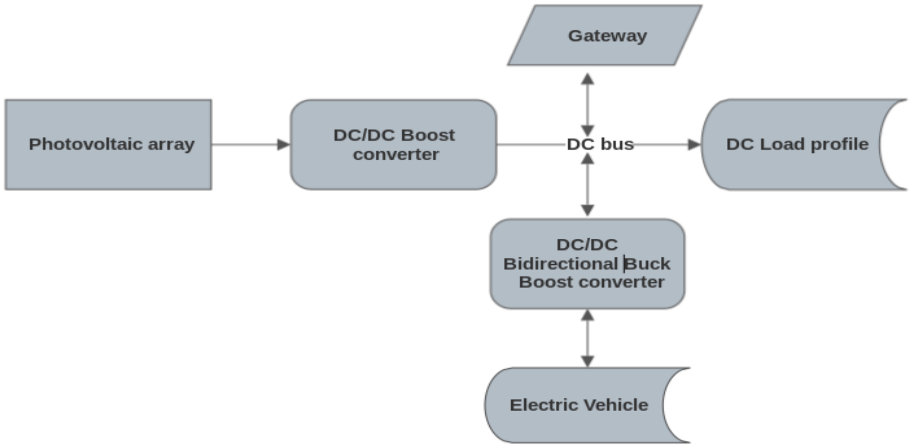

Figure 3.4: Schematic diagram of DC nanogrid-2

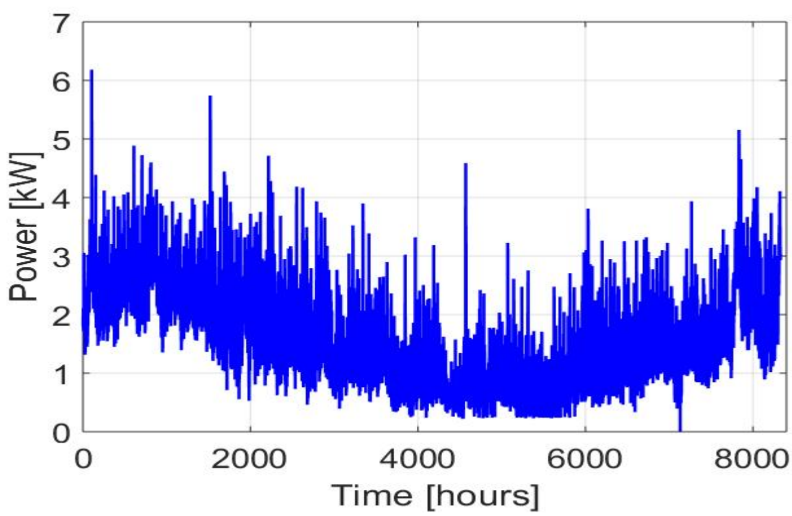

Figure 3.5: Load profile for Nanogrid 2

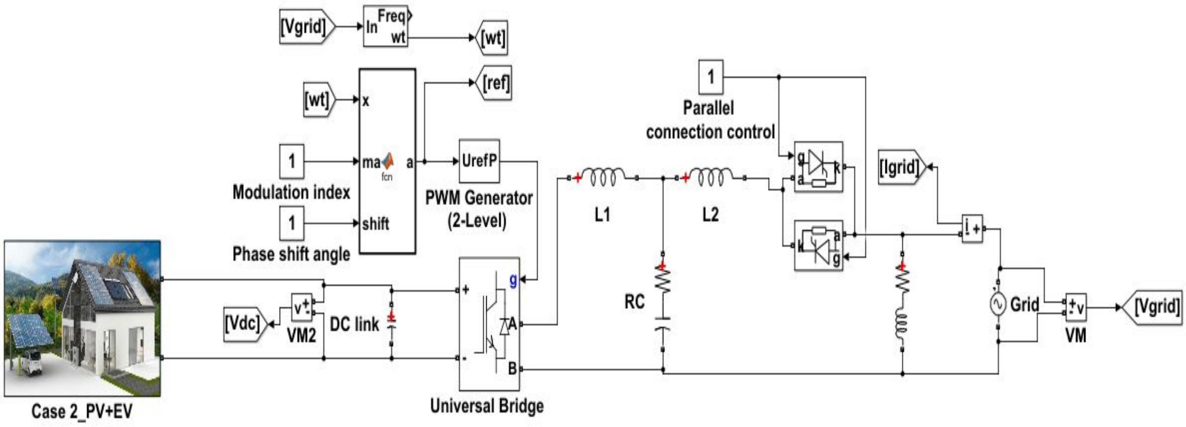

Figure 3.6: Model of grid connected DC nanogrid-2

3.1.3 DC nanogrid-3

DC nanogrid-3 is modelled considering only an electric vehicle. In this subsystem the renewable energy sources and batteries are not considered. Figure 3.7 shows the schematic diagram of the DC nanogrid-3 and Figure 3.9 shows the Matlab/Simulink/SimscapePowersystem model of the system. Details about the parameters of the nanogrid subsystem are given in Table 3.1 and the load profile of DC nanogrid-3 is shown in Figure 3.8.

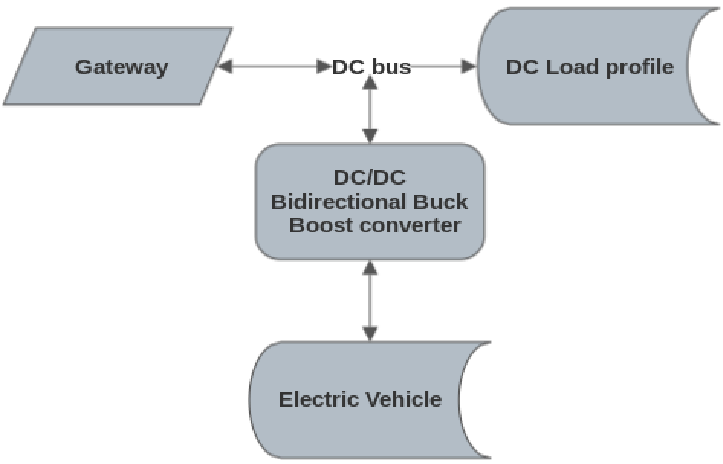

Figure 3.7: Schematic diagram of DC nanogrid-3

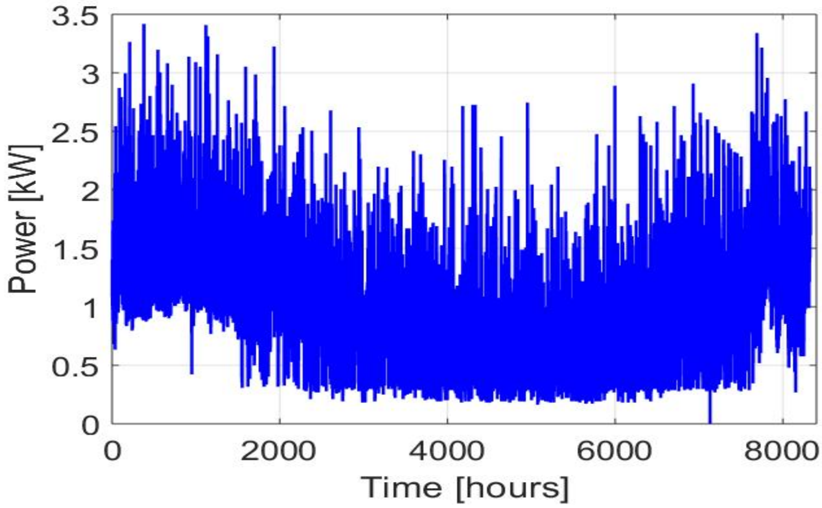

Figure 3.8: Load profile for Nanogrid 3

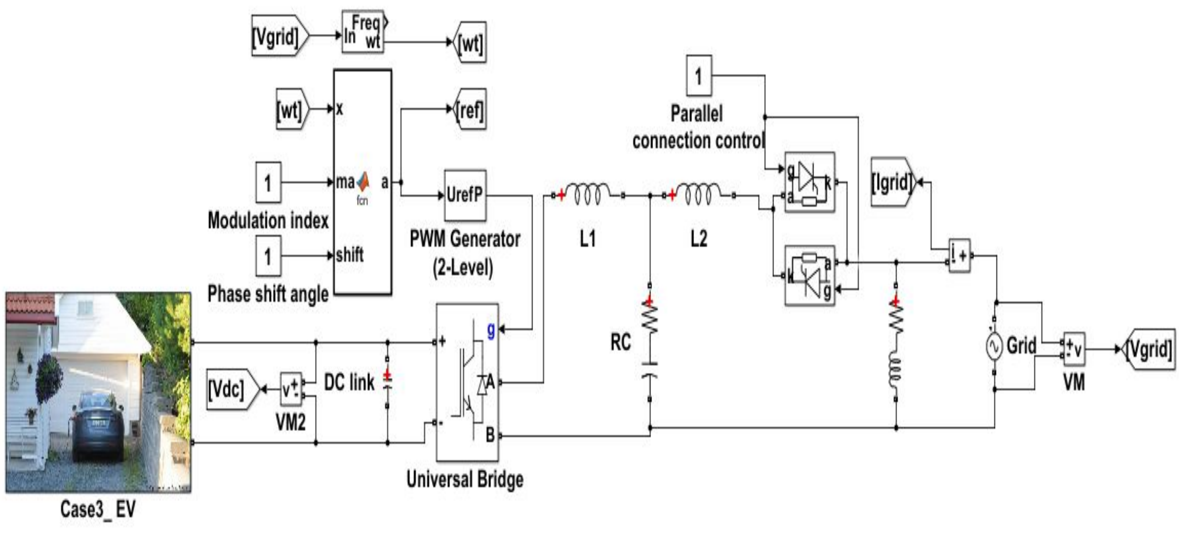

Figure 3.9: Model of grid connected DC nanogrid-3

3.1.4 DC nanogrid-4

DC nanogrid-4 is modelled with a PV array and a battery. Figure 3.10 shows the schematic diagram of the DC nanogrid-1. Details about the parameters of the nanogrid subsystem are given in Table 3.1. Figure 3.12 shows the model of grid connected DC nanogrid-4 and the load profile of DC nanogrid-4 is shown in Figure 3.11.

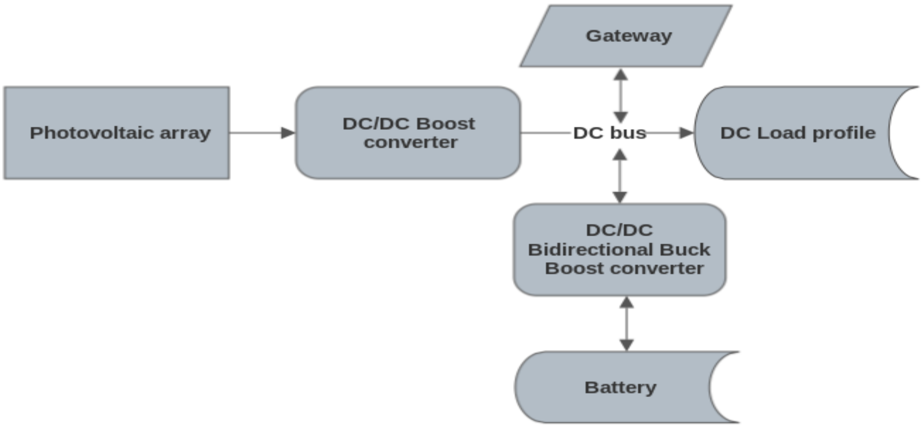

Figure 3.10: Schematic diagram of DC nanogrid-4

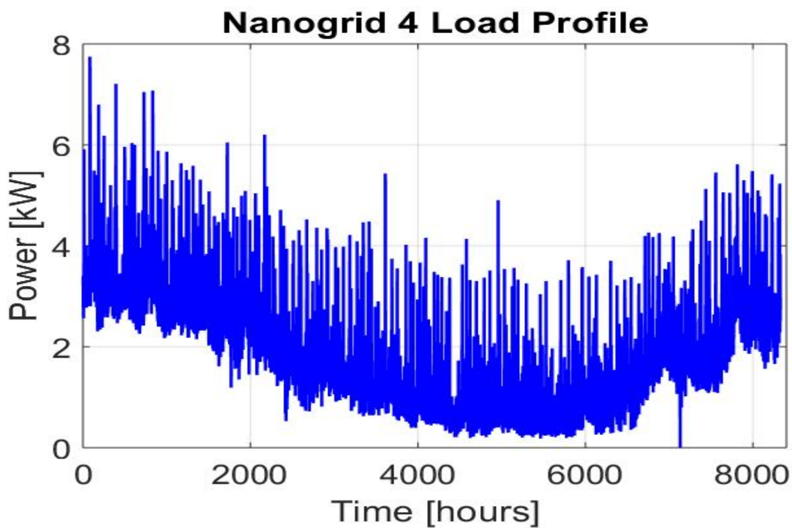

Figure 3.11: Load profile for Nanogrid 4

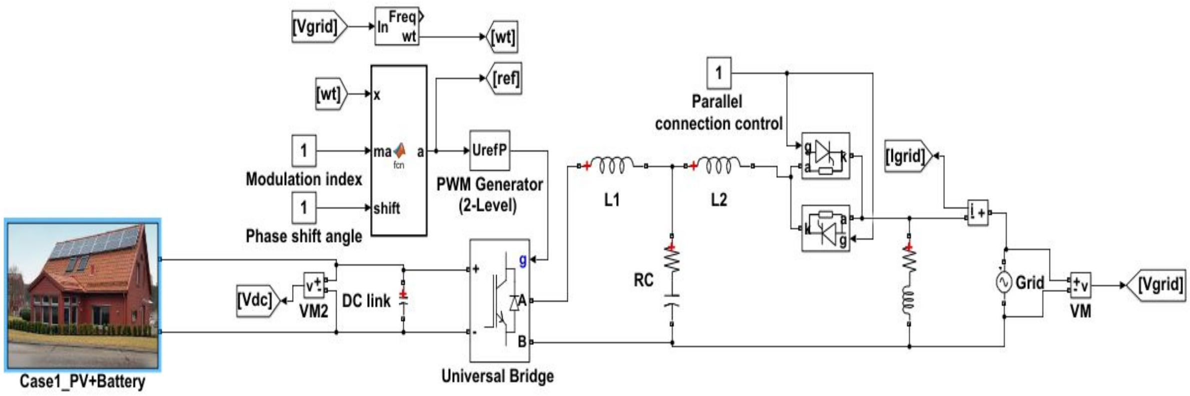

Figure 3.12: Model of grid connected DC nanogrid-4

3.1.5 DC nanogrid-5

DC nanogrid-5 is modelled with a PV array and 3 electric vehicles. An energy storage (battery) is not considered in this nanogrid. Figure 3.13 shows the schematic diagram of the DC nanogrid 5 and Figure 3.15 show the Matlab/Simulink/SimscapePowersystem model of grid connected system. Details about the parameters of the nanogrid subsystem are given in Table 3.1 and the load profile of DC nanogrid-5 is shown in Figure 3.14.

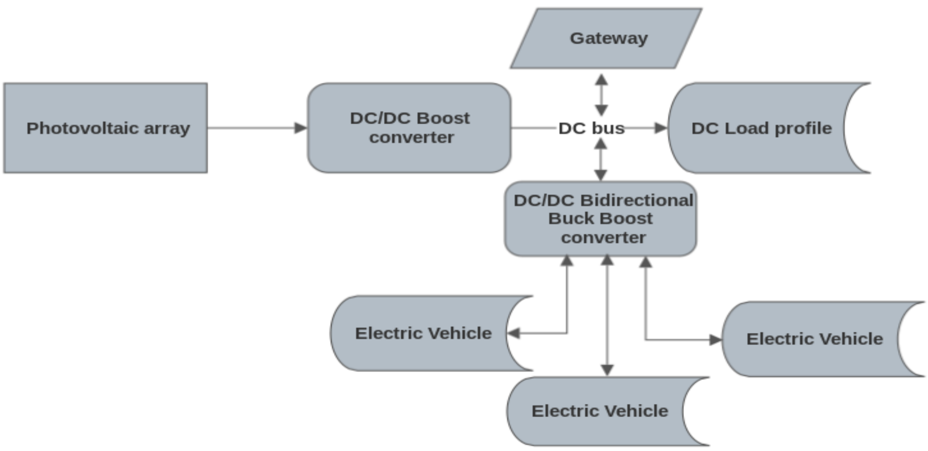

Figure 3.13: Schematic diagram of DC nanogrid-5

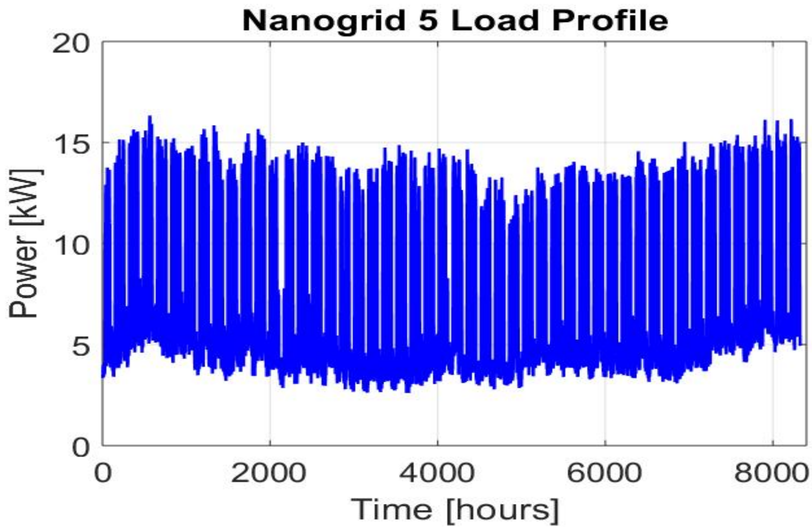

Figure 3.14: Load profile for Nanogrid 5 (Office building)

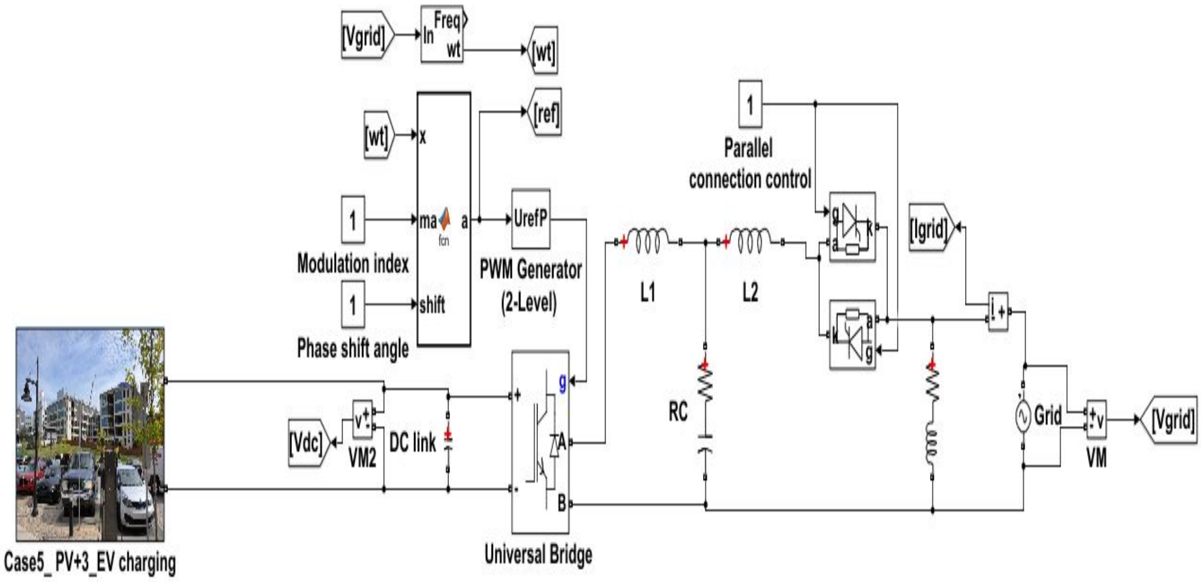

Figure 3.15: Model of grid connected DC nanogrid-5

3.2 Scenario 2: Microgrid made of inter-connected DC nanogrids

In this scenario, the individual nanogrids are interconnected such that it is possible to trade power between themselves. The nanogrids can be separately connected to the utility grid or they can have a single gateway to the utility grid that is controlled by an energy dispatch algorithm. This scenario is focused on analysing the performance of the individual nanogrids and the resulting microgrid.

3.2.1 DC microgrid

The DC microgrid is considered with the 5 nanogrid cases mentioned above. It includes the 4 residential buildings and 1 office building. These buildings have different energy consumption patterns. For example, the residential buildings usually have a peak load in the evening and low load during the daytime, but, the office building consumes a large amount of power during the daytime and less in the evening. Furthermore, the PV energy production is realised during the day, hence self sufficiency can be increased by directly using the produced energy during the day or by storing it for later usage. Respectively, coordination between the above mentioned nanogrids and taking advantage of their different load profile patterns by sharing energy can increase self sufficiency and self consumption in a DC microgrid.

All the terminals connected to the DC bus can be classified into two types: power terminals and slack terminals. The sources which either supply or consume power to or from the DC bus is considered as power terminals. Power terminals have no role in the voltage control of the bus. For example, the DC loads, PV panels working with MPPT mode and nearby buildings are power terminals. The function of a slack terminal source is to accommodate the power fluctuation caused by power terminals and maintain power balance and stable voltage. An energy storage system (battery) is an example of a slack terminal.

To protect the DC microgrid from abnormal conditions like sudden loss of PV energy, over voltage and under voltage it must be switched into grid connected mode. So the AC grid works as a slack terminal to control the voltage of the bus.

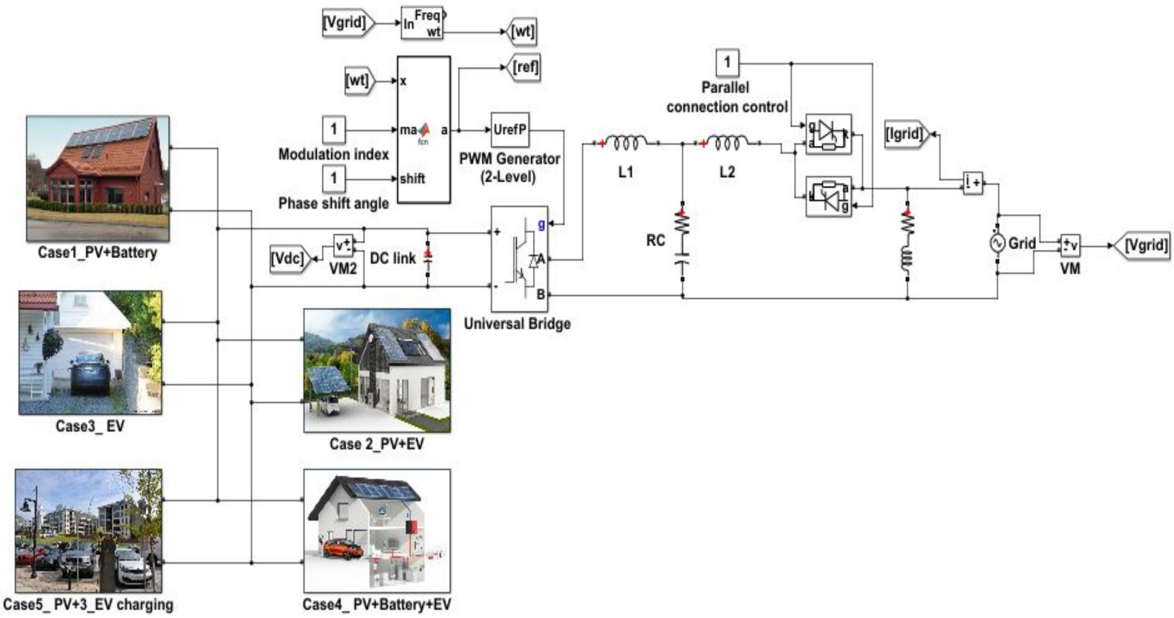

Figure 3.16: DC microgrid

3.3 Dispatch algorithm

3.3.1 Residential building dispatch algorithm

The dispatch algorithm for all household nanogrids is such that when the PV generated energy is greater than the load, the following priority list is used.

- **Load** - The load is covered first
- **Battery** - If a battery is connected and not full, it is charged next.
- **Electric vehicle** - If the battery is full or not available and an electric vehicle is available and not fully charged, it is charged with the excess
- **Grid** - If all the above options have been exhausted, the excess power is fed into the grid.

When PV energy is equal to the load, neither the battery nor the electrical vehicle (if available) will be charged or discharged. However, if the PV energy is less than the load, the same hierarchy is considered.

- **Load** - Feed all the PV generated energy to the load.
- **Battery** - If a battery is connected and not empty, it is discharged next.
- **Electric vehicle** - If battery is empty or not available and an electric vehicle is available and not empty, it is discharged to compensate the energy deficit
- **Grid** - If all the above options can not cover the energy deficit, additional power is obtained from the utility grid.

Both the electric vehicles and the battery can only be charged from excess PV energy.

3.3.2 Office buildings dispatch algorithm

The dispatch algorithm for the office building (nanogrid 5) is almost similar to that of household nanogrids except for the fact that the electric vehicles can also be charged from the utility grid and also that electric vehicles can not discharge to the load. If the PV generated energy is greater than the local load, the following priority list is used.

- **Load** - The load is covered first
- **Battery** - If a battery is connected and not full, it is charged next.
- **Electric vehicle** - If the battery is full or not available and an electric vehicle is available and not fully charged, it is charged with the excess PV energy at fast charging rate.
- **Grid** - If all the above options have been exhausted, the excess power is fed into the utility grid.

It should be noted that if the excess PV energy is greater than the local load but not sufficient to cover the charging of electric vehicles, the electric vehicles will charge from the utility grid at a much lower charging rate. If PV energy is equal to the load, the battery will not be charged or discharged but if the electric vehicles are not fully charged, they will be charged slowly by the utility grid. However, if the

PV energy is less than the load, the same hierarchy is considered.

- **Load** - Feed all the PV generated energy to the load.
- **Battery** - If a battery is connected and not empty, it is discharged next.
- **Electric vehicle** - Electric vehicles are charged slowly from the utility grid until they are fully charged.
- **Utility Grid** - Covers all remaining energy deficits.

3.3.3 Microgrid dispatch algorithm

When all the nanogrids are interconnected to form a microgrid, they will continue following the above mentioned dispatch algorithm except that before any nanogrid import power from the utility grid, the controller checks to see if there is any nanogrid with a power deficit. If there is, the excess power is supplied to the nanogrid with a deficit instead of sending to the utility grid. Likewise, if any nanogrid has a deficit, priority is given to any excess PV energy from other nanogrids before importing from the utility grid.

3.3.4 Charging and discharging limits

The battery that is to be used in the simulations is the same battery that was installed at the RISE research Villa in Borås. The data sheet for the battery is attached in Appendix 1: Figure A.1. The maximum charging rate is 6.9 kWh. However, in the simulations, a maximum charge rate of half the installed capacity is selected so as not to stress the battery and the power electronic circuits. The electric vehicles to be used in the simulations consists of a BMW i3, Nissan leaf and Tesla model S. The characteristics of these cars can be found in Appendix 1: Figure A.2. When the electric vehicles are charging from excess PV energy, they charge at the fastest possible charging rate. However, when charging from the utility grid, it charges slowly at such a rate that it can charge from 40% to 90% in 9 hours. 40% is the lowest allowed SOC the electric vehicle can discharge to when connected to a nanogrid. The 8 hours are calculated from the time the electric vehicle is connected to a charger at work to the time it is disconnected after work. This modification was introduced to cover winter times which have limited generation of PV energy. The charging limit is the same as the discharging limit for the storage battery and for electric vehicle, the discharge limit is equivalent to the fastest charging limit. Table 3.2 shows the limits to be used.

Batteries only charge from PV energy and not from the microgrid energy or the utility grid. According to JRC technical reports, in Sweden a vehicle travels an average of 44.24km per day[29]. The energy lost travelling is also incorporated on a daily basis using the energy consumption in Appendix 1: Figure A.2.

Table 3.2: Charging limits from different sources

Medium	PV Charging usage [kWh]	Utility grid Charging usage [kWh]	Microgrid Charging usage [kWh]
Nanogrid 1 Battery	3.6	–	–
Nanogrid 4 Battery	6.75	–	–
BMW	48	2.05	25
Nissan Leaf	7.5	2.05	4.8
Tesla model S	144	2.95	73.5

3.4 Solar PV profile

The solar PV data to be used in this study was obtained at a RISE research villa in Borås. The data was measured for a whole year in 2016 for a 3.6 kWp solar PV installation. However, Figure 3.17 shows a scaled version of the data for a 1 kWp installation. The study, therefore, assumes that all the nanogrids are to be located in Borås and their respective solar panel installations will be of the same nature as those at the research villa and will be exposed to the same solar irradiance. Since the nanogrids will have different attributes, for the different PV installations, the profile shown in Figure 3.17 will simply be linearly called up to match the proposed installation size. The PV profile had notable missing data from the 5th of January to the 7th of January 2016. There was also missing data between 21 March to 31 March, 21 - 23 August, 27 September and 3 - 7 October 2016. However, for these periods, estimated values were used. However, from 14 October to 11 November as can be seen in Figure 3.17, PV power values are zeros yet all other measurements were registered. It is therefore not clear if its due to missing data or if there was no solar irradiance which is less likely to be the case.

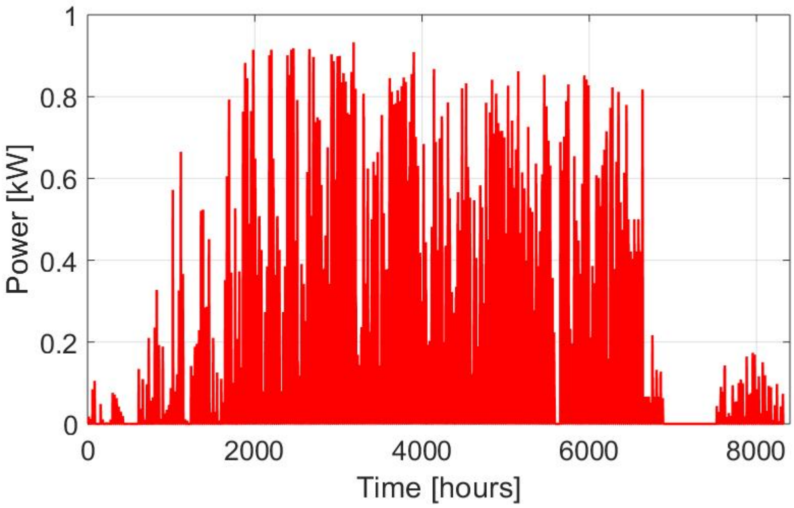

Figure 3.17: PV profile for a 1kWp solar PV installation

4

Blockchain & Microgrid

4.1 Swedish power market

At present half of the electricity production in Sweden comes from renewable energy sources such as hydropower, biofuels and wind power. Sweden consumes about 150 TWh of electricity per year. A large part of power production in Sweden depends on hydropower and nuclear power. The major electricity producers in Sweden are Vattenfall, Fortum, E.on and Sydkraft.

In 2009 the Swedish parliament implemented a new climate and energy policy. The aim of the policy was that by 2020, 50% of the total energy consumption should be contributed by renewable energy sources. Sweden managed to reach its goal by 2012. In 2015 total electricity production from renewable sources was 57%. Figure 4.1 shows the electricity production in Sweden in the year 2015. As a next step, the energy commission submitted another report in January 2017. The report is known as Energy of the Future. Main target and objective of that report is to produce 100% renewable electricity production by the year 2040. It is also specially mentioning that it is not a deadline for banning nuclear power plants. Also, another target is to achieve negative emission by the year 2045. It means no net emissions of greenhouse gases into the atmosphere by the year 2045. So in the future, the main energy production types will change and become more distributed. Corresponding to that, the grid structure may also advance in different ways and become more decentralised. As an outcome of this progress, the Swedish electricity market may also require some changes[30].

The inspectorate is the central regulatory body for the Swedish energy markets. It is an authority under the ministry of enterprise, energy and communications. Swedish electricity, natural gas and district heating markets are supervised by them. One of the fundamental duty of the Inspectorate is to improve the functioning and efficiency of these markets. The budget of the Inspectorate is decided by the Swedish parliament and the government[30].

The electricity grid in Sweden is divided into national, regional and local networks. Where the national grid is with high voltage levels between 220-400 kV lines, the regional grid has a voltage level of 40-130kV and the local grid has a maximum 40 kV. The frequency needs to be at 50 Hz[30]. The national grid is owned and managed by Svenska Kraftnät. It is a state-owned public utility and is responsible for transmitting electricity from the major power stations to regional electrical grids via the national grids. While the regional and local networks are managed and expanded through a network concession. This means that the state has given the task to one or more actors to run, maintain and manage the regional network. Figure 4.1 shows the electricity production in Sweden in the year 2015 [31].

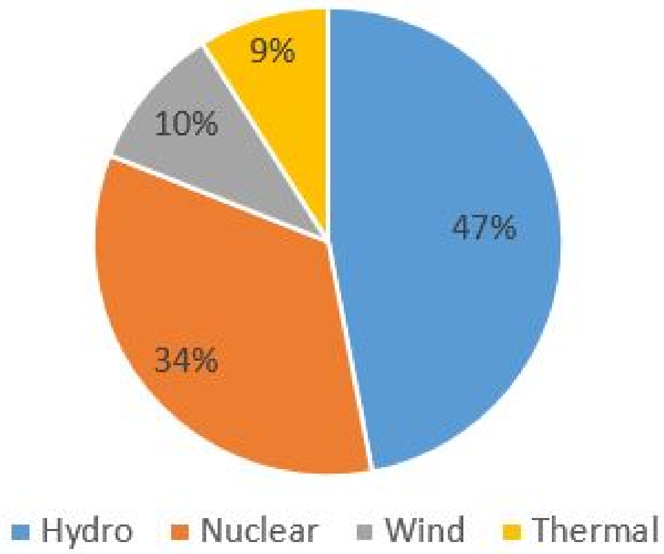

Figure 4.1: Total electricity production in Sweden 2015

- **Hydropower** - Hydropower plays an important role in the Swedish energy markets. Approximately 47% of power is generated by hydroelectric power plants. In 2015 hydropower production was close to 75 TWh, which was higher compared to the year 2014. In 2014 the total hydropower production was 63 TWh. The hydropower production varies over the years according to the availability of water. The lowest rate of hydropower production in the past 20 years was 41 TWh. The largest hydropower plant is located in the north of Sweden predominantly located on "Lule river".
- **Nuclear power** - The future of nuclear plants in Sweden is unclear. Currently, 34% of the Swedish electricity is produced by the nuclear plants. In 2015 Swedish nuclear power plants generated 54 TWh of electricity. This electricity production rate is lower compared to previous years. Currently, there are 10 nuclear reactors and they have the ability to produce 65-67 TWhr per year [33]. These reactors are spread out on 3 power stations named Ringhals Nuclear Power Plant, Oskarshamn Nuclear Power Plant and Forsmark Nuclear Power Plant. There were totally 12 nuclear reactors before 2005. But in 1999 and 2005 2 reactors at the Barsebäck nuclear power plant were decommissioned and also in 2015 Sweden decided to close down 4 older reactors by 2020.
- **Wind power** - Currently, Sweden is the sixth biggest wind power producer in Europe [32]. In 2015, 10% of the Swedish electricity was generated from wind power. In 2015 approximately 16 TWh of electricity was generated from domestic wind power resources. Electricity from wind power continued to

increase sharply between 2014 and 2015. At the beginning of 2016, the total number of wind turbines was 3174 with a total installed power of 5840 MW [33]. Sweden is going to invest 16 billion kronor in a project which consist of 400 wind turbines in seven wind farms. The wind farms are located in Jämtland and Västernorrland counties. The project will start by 2020 having a capacity of 4 GW [34].

- **Thermal power** - In 2015, 9% of the Swedish electricity was from combustion-based power. Approximately 13 TWh of electricity is accounted for combustion-based electricity production. The major portion of fuel used for thermal based electricity production is biomass. About 72% is from biomass, 11% is from coal and the remaining from natural gas, oil etc
- **Solar power** - Solar PV energy produces electricity from sunlight, which can be fed into the mains electricity supply of a building or sold to the utility grid. There is a misconception that it is necessary to have sunnier climates for solar panels to work effectively. Solar panels perform effectively and efficiently in colder climates where the sun shines. The Swedish winter is cold and dark but Sweden has long summer days. So Sweden can produce energy from solar power. There are lots of researchers going on to improve the efficiency of solar panel and how to effectively implement that with the utility grid.
  Currently, electricity produced using photovoltaic is very small but is growing very quickly. At the end of 2014, the total installed photovoltaic capacity was around 60MW and it improved to 141 MW in April 2017. Approximately 0.06% of Sweden's total electricity production is from solar power[33].

4.2 Why blockchain?

Tech people consider blockchain technology as the biggest innovation after the internet. They believe this technology is going to be the next big thing in the tech world as well as in other sectors. According to World Economic Forum, more than 25 countries are investing in blockchain technology, filing more than 2500 patents and investing $1.3 billion. However, the implementation of blockchain technology would be slower as it would be a big challenge to displace the existing technology platforms [35] [36]. The blockchain is nothing but a process of exchanging money and in the future, it could expand its scope, allowing transfer of other things apart from assets.

4.2.1 Functional principles of blockchain

Blockchain technology is a special form of verifying transactions. It is in the shape of chained data records (decentralised and distributed register) called blocks. The transactions are done at a very low transaction cost. Every participant in this distributed network shares a same copy of the records. The distinct feature of distributed payment system from the conventional centralised payments system is that of not having a central server. Also, the records are available only at the central server. Additionally, participants of this network can conduct peer to peer transactions. Figure 4.2 shows a centralised payment system and distributed payment system components and their interaction.

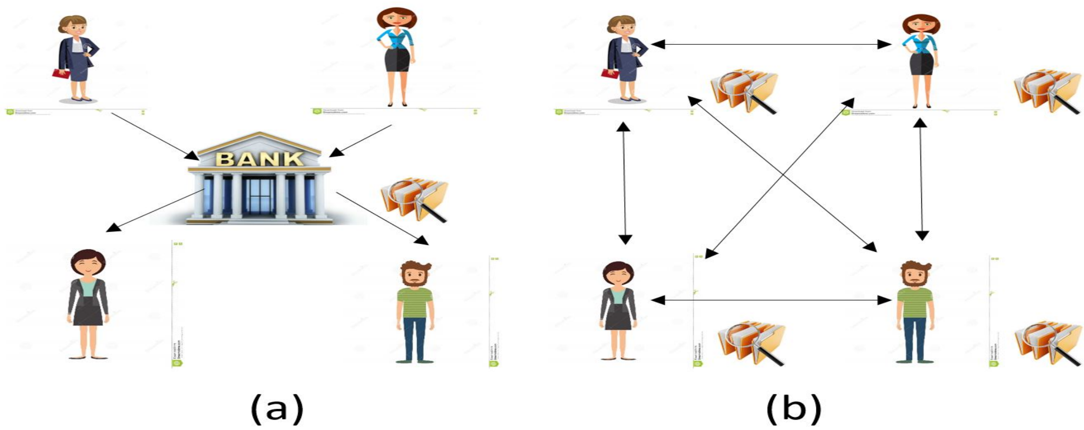

Figure 4.2: (a) Centralised payment system (b) Distributed payment system

As shown in Figure 4.2 in a centralised payment system, only the bank holds the list of all transaction records, for instance, who transferred money to which account. However, in a distributed payment system all participants are connected to each other through the internet and everyone has the same copies of the list of records.

In the traditional transaction there is an intermediary platform which controls and analyses all the data. Also, it has some transaction charges. But in a blockchain system, the transaction is carried out directly between providers and their consumers. All the transactions are stored on a distributed blockchain with all relevant information being stored. All the transactions are made on the basis of smart contracts. Where a smart contract is a predefined individual set of rules regarding the quality, quantity and price etc. Also, blockchain is a largely automated, decentralised transaction model with no need for third party interaction.

Advantages of blockchain technology

- **Empowered users** - All the information and data are controlled by each member of the system. This platform allows users to have their control over their information and transactions.
- **Decentralised Data** - The decentralised data make the system much more secure than others. Data is not stored on a single computer rather it follows a unique principle of saving the data.
- **Security** - It is a major concern for all sorts of users while exchanging the data and transactions. In the financial domain, this aspect is the prime when it comes to transactions between two users. Blockchain technology makes the transaction much safer. This feature of the blockchain will create huge demands in the near future when it joins the mainstream.
- **Information validation** - The blockchain technology is also helpful in validating the information and controlling it in the digital space. It will be useful

for having secured transactions and the transactions will not be processed if the validation process is not completed or miss any defined elements.

- **Transparency** - When it comes to peer to peer transactions, it should be more transparent. Blockchain transactions can't be tampered or deleted post-execution.
- **Reduce Process Time** - The transactions over blockchain platform would consume less time compared to the existing platforms. There won't be any centrally authorised process to complete all the transactions.

Ethereum & Smart Contracts

Ethereum is an open software platform based on blockchain technology that enables developers to build and deploy decentralized applications [37].

A smart contract can be explained as a computer program that runs on the blockchain. A smart contract consists of program code, a storage file, and an account balance. Any user can create a contract by posting a transaction to the blockchain. The program code of a contract is fixed when the contract is created and cannot be changed [38] [39].

4.3 Blockchain application in microgrid

Some of the blockchain application in a microgrid are explained below. Most of them are still under development or in the testing phase.

- **Power Ledger** - The aim of the project is to create a trade market for consumers to buy and sell renewable energy directly between one another using blockchain platform. Also, it targets to create a positive effect on costs and the climate. The focus is to create a transparent, auditable and automated record of energy generation and consumption which will result in energy savings. Power Ledger is an Australian based company and their first project is planning at the United States, Northwestern University Evanston campus [40].
- **PWR.Company** - The aim of the project is to build a blockchain solution that effectively helps the prosumer to collect, store and share their energy with the house to house level. The solution includes deep cycle batteries for power storage to stabilise the grid. Furthermore, it is focused to eliminate the influence of middleman to save the consumer money, maximise the return for prosumers and offers more renewable energy to neighbourhoods. The project currently uses the Etherum platform and trying to make their own version of energy based cryptocurrency in the future [41].
- **Key2Energy** - The aim of this project is to provide self-generated PV energy to tenants in multi-apartment houses with an aim to reduce the interaction of the utility grid. Mainly two agents are involved in this process. The first one tries to maximise the revenues for the house by selling the produced solar energy on the local market at best possible prices. The second one tries to minimize the cost of shared electricity. This project is a collaboration with

Fronius International, Grid Singularity, IIBW and the Viennese Municipal Department 20 – Energy Planning [42].

- **LO3 Energy-Transactive grid and Brooklyn Microgrid** - LO3 Energy is a startup that brands itself as a "transactive energy company." It is preparing to expand internationally after building the world's first blockchain microgrid. LO3 Energy developed the transactive grid platform, that is based on Etherum and smart contracts. It enables peer to peer energy transactions, control of their energy sources for grid balancing and other uses. The LO3's Brooklyn microgrid (BMG) project, demonstrates the use of blockchain-enabled energy trading among a small group of residents, where the participants can sell the surplus solar PV energy to their neighbours. BMG is defined as a for-profit corporate entity that can positively impact society, workers, the community and the environment. BMG is currently owned by LO3 Energy. Once BMG is fully developed, LO3 will sell or gift shares of BMG to local organizations and individuals living in the Brooklyn community. Ultimately, the microgrid system will be truly community-owned and managed [43].
- **SolarCoin** - It is a digital asset that aims to enhance the production of solar energy. The aim of this project is to provide an inspiration to produce more solar electricity globally by rewarding the generators of solar electricity. SolarCoin is designed to reduce the cost of electricity, thereby reducing the payback time of a solar panel installation. Each SolarCoin in circulation represents 1 MWh of solar electricity generation [38].

Some of the other blockchain projects related to microgrids are Dajie, Share & Charge, NRGcoin, TheSunExchange, Bankymoon, Electron and PONTON Gridchain and Enerchain etc.

Limitation of blockchain technology

Blockchain has many advantages and are discussed at the beginning of this chapter. This technology is still evolving so there are some limitations right now. Some of them are discussed below.

- **Complexity** - All blockchain transactions are digitally signed. The generation and verification of digital signatures are complex.
- **Human error** - There are some chances to theft/loss of private keys.
- **Unavoidable security flaw** - There is a risk of 51% attacks. Also, some chances to IS integration.
- **Regulations** - Government should create rules and regulation for the efficient use of blockchain technology in energy sector. Currently its hard to find any regulations or standards to follow.

4.4 Proposed microgrid energy price

The pricing model for peer to peer energy trading should be favourable to both parties for block chain energy management to work. In this study, a fixed utility grid price is 1.4 SEK/kWh as in Table 2.3. The amount of money for selling excess PV energy to the utility grid is a result of adding the selling price, income for selling to grid, green electrical certificate, PV tax return and the guarantee of origin. The total value is 1.302 SEK/kWh. However, the green electrical certificates is only for a maximum of 15 years. Considering that the life span of PV installation is 30years, if the electrical certificates is scaled down, it is reduced by half from 0.147 SEK to 0.0735. Therefore, the average price of selling energy to the grid is 1.2334 SEK/kWh. Therefore, for it to be favourable to both parties, the price of microgrid energy should be in between the grid buying price and the average selling price to the grid. The proposed price is therefore (1.4 + 1.2285)/2 which is equal to 1.314 SEK/kWh.

5

Results

5.1 Scenario 1

5.1.1 DC nanogrid-1

Nanogrid 1 was modelled in Matlab as specified in Chapter 3. The flow of energy for the whole year in presented in Figure 5.1. For a clear analysis, a typical working day during the summer was selected and an extract for the data was made.

The selected date is Tuesday 20th of June 2016 which is the PV energy data's summer solstice and the plots are shown in Figure 5.2 for analysis. Basing on the power flow control algorithm in Chapter 3, Figure 5.2 shows that from the beginning of the day, the load is supplied by the battery which discharges continuously from a SOC of just above 30% to 15% which is the lowest acceptable SOC three hours later. From the moment the battery runs out, the load starts getting power from the electric vehicle and the PV energy that is generated up until the electric vehicle is disconnected. Since the date selected is a normal working day, the electric vehicle is disconnected from the system at 7am as the owner leaves for work and then reconnected at 7pm when the owner returns from work as shown in the diagram.

When the generated PV energy exceeds the load, the battery begins to charge. Since the date selected is the summer solstice, PV energy is generated for the longest number of hours as compared to any other day. It can also be seen that the nanogrid begins to send some power to the grid whilst the battery is still charging. This is due to that the battery has a charging limit. When the electric vehicle was reconnected, PV energy generation was still above the load hence the electric vehicle began to charge up until the PV energy was lower than the load since the EV can only charge from PV energy. It can also be seen that the intake from the grid is greatly minimised in summer as no power was taken from the grid on Tuesday, 20th of June 2016. It therefore means that even if the nanogrid is interconnected with other nanogrids, on this particular date, nanogrid 1 will not import any power from any nanogrid. If possible, it can sell excess power to nanogrids with power deficits.

The usage of generated PV energy for a year is shown in Figure 5.3. Since the EV is charged at the workplace till full and only discharges when travelling from work back home, a small amount of energy is used to charge the EV. Also, the electric vehicles are connected very late in the night hence there are a few summer

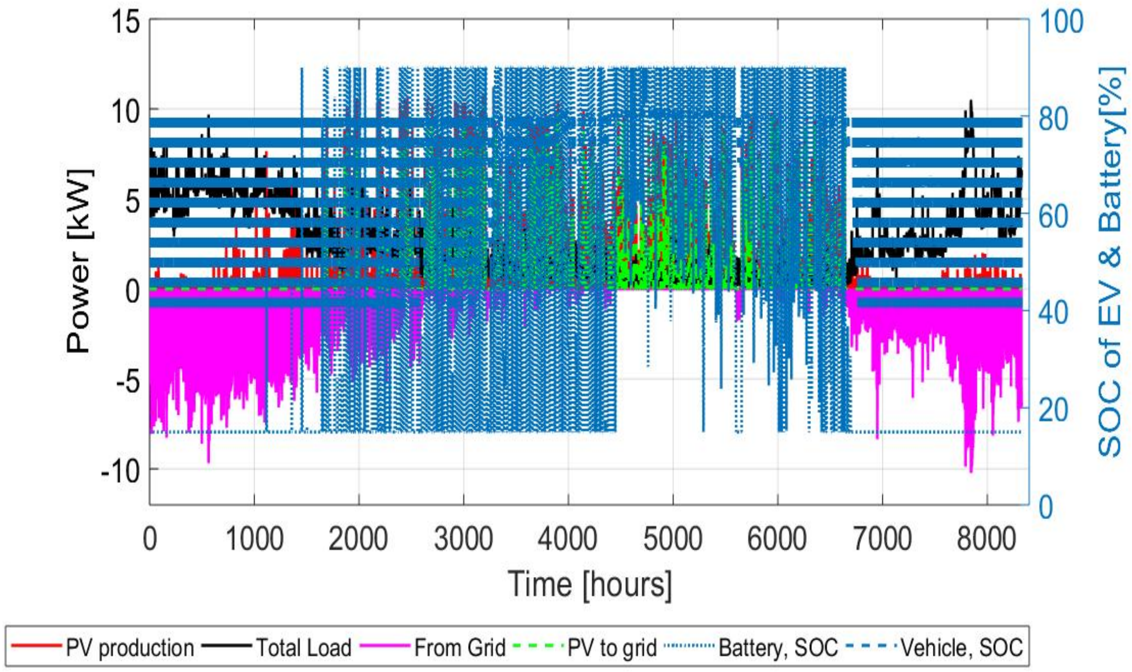

Figure 5.1: Nanogrid 1 flow of energy for one year

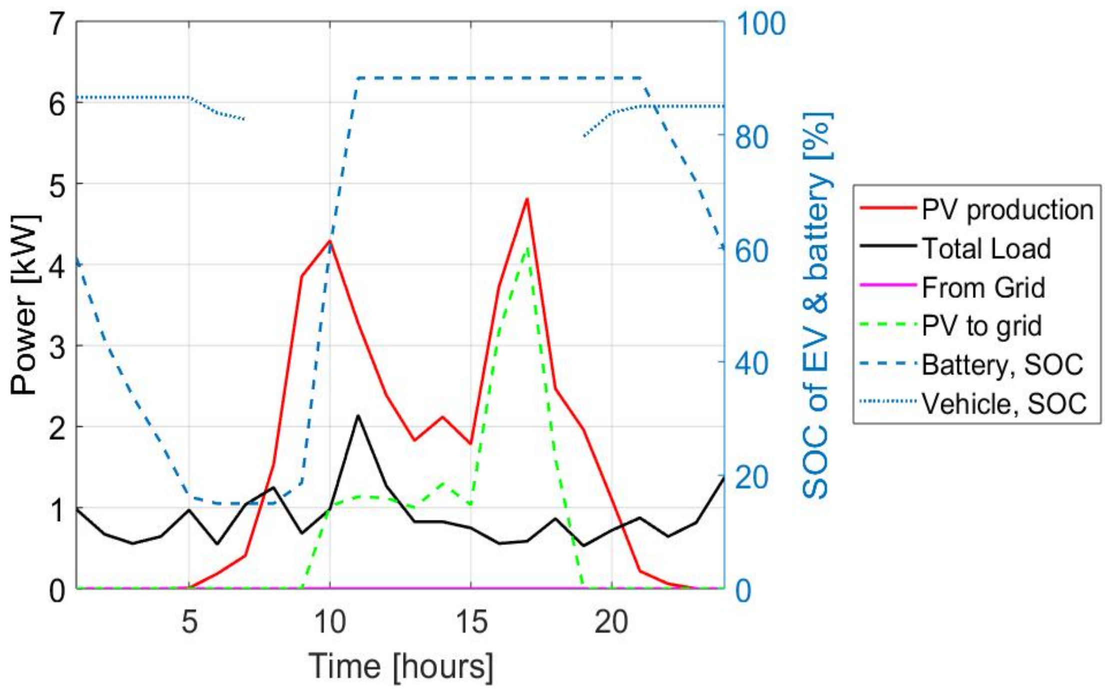

Figure 5.2: Nanogrid 1 flow of energy for one day (Tuesday 20th June 2016.) The electric vehicle is disconnected as it is driven to work from 7a.m. to 7 p.m.

days when the PV energy is higher than the load by the time the EV is connected.

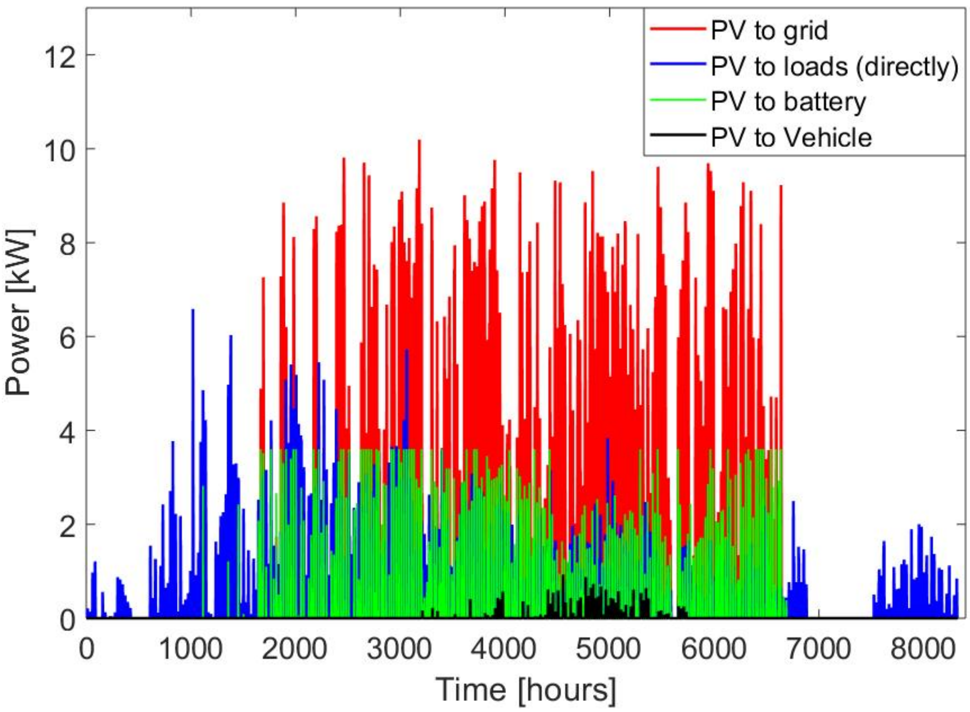

Figure 5.3: The usage of generated PV energy for a year

For further analysis, Tuesday 20 June was selected again and the diagram is shown in Figure 5.4. The figure shows that the PV energy generated is firstly fed to the load and when there is any excess, it is used to charge the battery after which the excess is sent to the grid. If an EV is connected, instead of sending the power to the grid, the power is channelled to charge the EV, in the case that the EV is not fully charged.

The installation of a PV energy system requires a substantial capital outlay. However, the subsidies introduced by the Swedish government as described in Chapter 2 makes it affordable. The payback period is calculated basing on the levelized cost of energy LCOE which is described in detail in Chapter 2. Nanogrid 1 has a payback period of 16 years as shown in the Figure 5.5. The payback period is affected by the cost of converters which needs to be replaced after 15 years. Furthermore, the battery also has a limited lifespan calculated from a 3000 cycles lifetime at 80% DOD. For nanogrid 1, the battery is replaced when it reaches the calculated lifespan of 18 years which also happens to be the same for nanogrid 4. Figure 5.6 shows that the greater part of the calculated payback money is actually realised through self-consumption followed by PV energy tax and then money paid by the utility grid for selling power to it.

Nanogrid 1 was modelled with PV energy, battery and an electric vehicle. On the other hand, as shown in Table 3.1, nanogrid 2 has a PV array and an EV, nanogrid

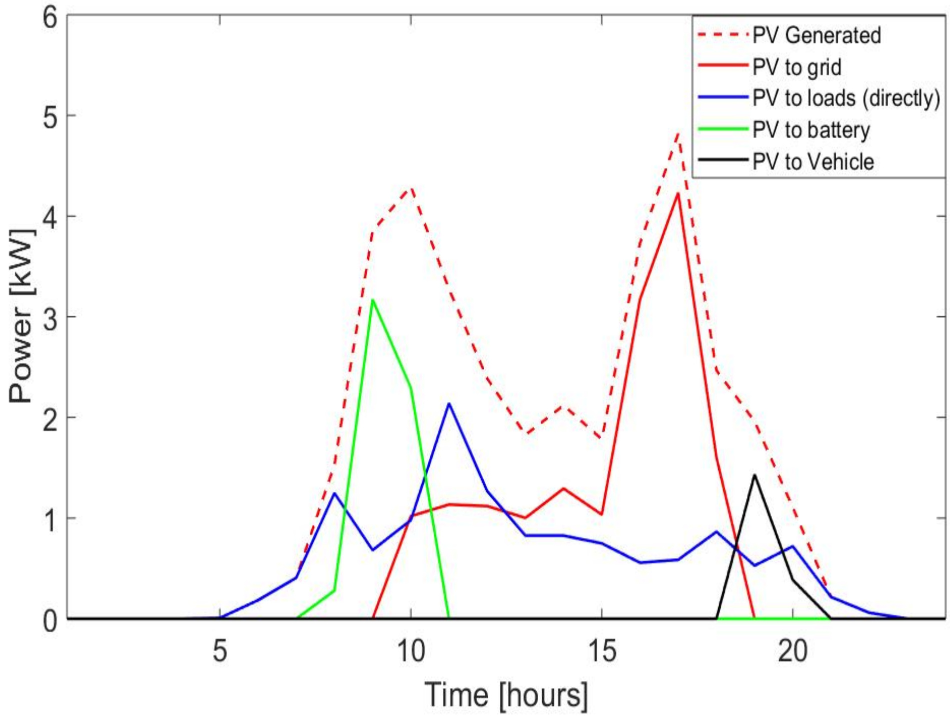

Figure 5.4: Nanogrid 1 usage of generated PV energy for a day

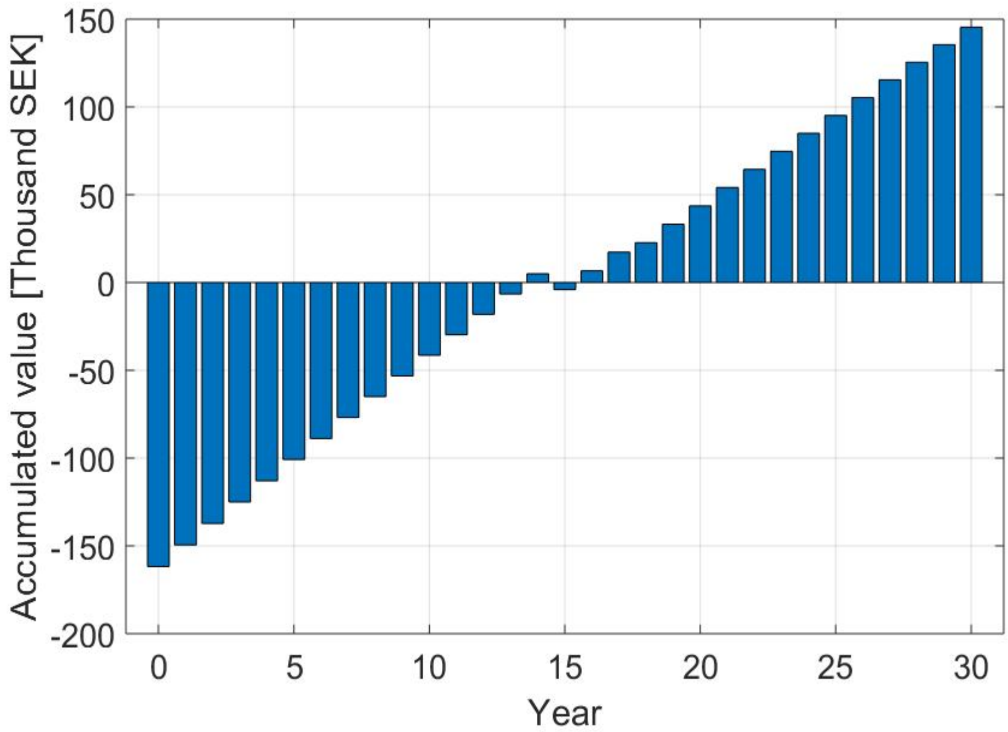

Figure 5.5: Nanogrid 1 payback period

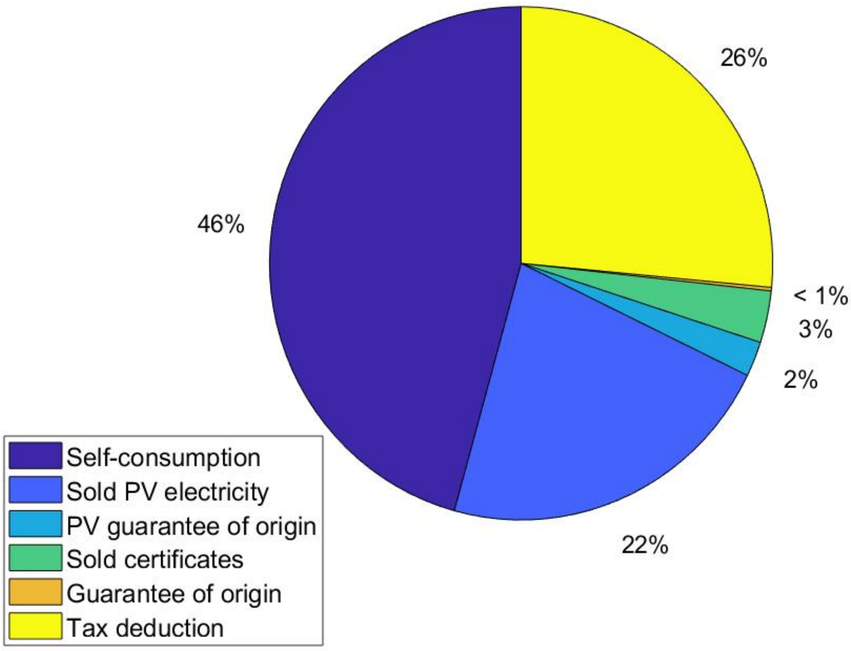

Figure 5.6: Nanogrid 1 PV energy income distribution

3 has just an EV, nanogrid 4 has PV energy and battery, and lastly, nanogrid 5 has just PV energy installed. All the nanogrids have different loads hence the design parameters regarding the sizes of PV energy, storage batteries or even the EV are all different. In order to analyse the impact of having these different setups, nanogrid one was taken and the load and installation design parameters were kept constant whilst varying the structure following that of the other nanogrids. The performance of the nanogrid was tabulated in Table 5.1 which shows the impact of having a battery or an EV.

Table 5.1 shows that if the electric vehicle is removed from nanogrid one which is equipped with just PV energy and a battery, the annual energy from the grid drastically increases by 22.44%. This also increases the cost of energy from the grid. However, the overall cost of energy decreases by 1.13%. This is so because of the electric vehicle charging and discharging losses.

In the second scenario of PV energy and EV as in nanogrid 2, PV energy to grid increases drastically, by 18.16%, as the PV energy can no longer be stored during the day. Also, the energy being taken from the connected EV also increases, thereby increasing the total cost of energy acquired from outside the system. A notable decrease of SC and SS is realised as more power is sent to the grid instead. Nevertheless, the payback period decreases due to the absence of a battery which needs to be installed twice to cover the installation life span of 30 years. The 4th scenario is considered with solar PV panel. So, no EV or battery is available in the 4th scenario. The SC further decreases by 11.48 percentage points from the initial state whilst at the same time, the SS falls by 5.64 percentage points. For the final scenario with just an EV, the power intake from the grid increases as expected. However, due to charging and discharging losses, this scenario is not financially sound unless if it is used for peak shaving.
Nanogrid 2 to 4 were modelled in the same manner nanogrid 1 was modelled and the obtained performance values are shown in Table 5.2

Table 5.1: Nanogrids' variation impact on performance

	PV energy, Battery & EV	PV energy & Battery	PV energy & EV	PV energy	EV
Energy from grid[kWh]	12,231	22.44%	2.27%	29.33%	24.07%
PV energy to grid [kWh]	5,218	2.99%	18.16%	21.28%	-
PV energy to battery [kWh]	954	0%	-	-	-
PV energy to Vehicle[kWh]	155.9	-	4.55%	-	-
Vehicle to grid energy [kWh]	2,757	-	23.84%	-	30.60%
Self consumption (SC) [%]	42.5	-1.7%	-9.7%	-11.48%	-
Self sufficiency (SS) [%]	20.9	-0.84%	-4.77%	-5.64%	-
Annual Energy cost from grid [SEK]	17,223	21.73%	1.67%	28.58%	23.35%
Annual Energy cost from EV [SEK]	3,981	-	23.84%	-	30.60%
Total external energy cost [SEK/yr]	21,204	-1.13%	5.84%	4.44%	24.71%
Pay-back period [years]	16	16	14	16	-

5.1.2 DC nanogrid-5

As for nanogrid 5, the obtained plots are shown since this nanogrid had a different power flow controlling algorithm because all-electric vehicles were supposed to charge at work. The power flow plots for nanogrid 5 are shown in Figure 5.7.

A different summer day was selected for better analysis and also since unlike the other household load data that was measured in 2013, the load data for nanogrid

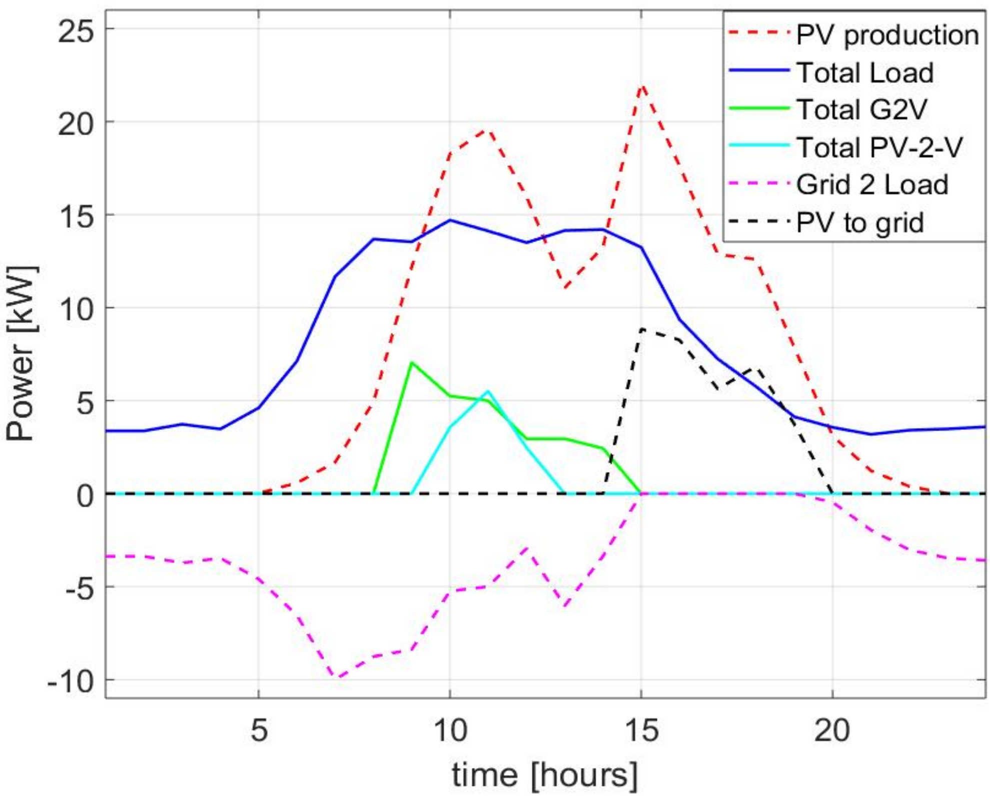

Figure 5.7: Nanogrid 5 flow of energy for 24 hours on a summer day (Monday 19 June 2016)

5 was measured in 2015. The selected date is Monday 19th of June 2016 (basing on the PV energy data that was measured in 2016). Unlike other nanogrids where electric vehicles are only charged from the PV panels, in nanogrid 5, the electric vehicles commence charging from the moment they are connected. It is only after the electric vehicles are fully charged that excess PV energy is sent to the utility grid as shown in Figure 5.7. However, it should be noted that the blue curve for total load does not include electric vehicles. This is also the reason why there is power intake from the grid when PV energy is above the internal load curve. Both Figure 5.8 and Figure 5.9 also confirms this switching algorithm.
The installation of PV energy on a commercial building is more expensive considering the size of the installation but the cost per unit size is far too less as compared to ordinary installations as explained in Chapter 2. Even though the discount rate is higher, the payback period is lesser and in this case, it is just 10 years as shown in Figure 5.10. Figure 5.11 then shows that the major contributor to the PV income is the self-consumption followed by PV energy taxes, PV energy sold to the utility grid and the PV energy sold to electric vehicle owners charging their vehicles at work.

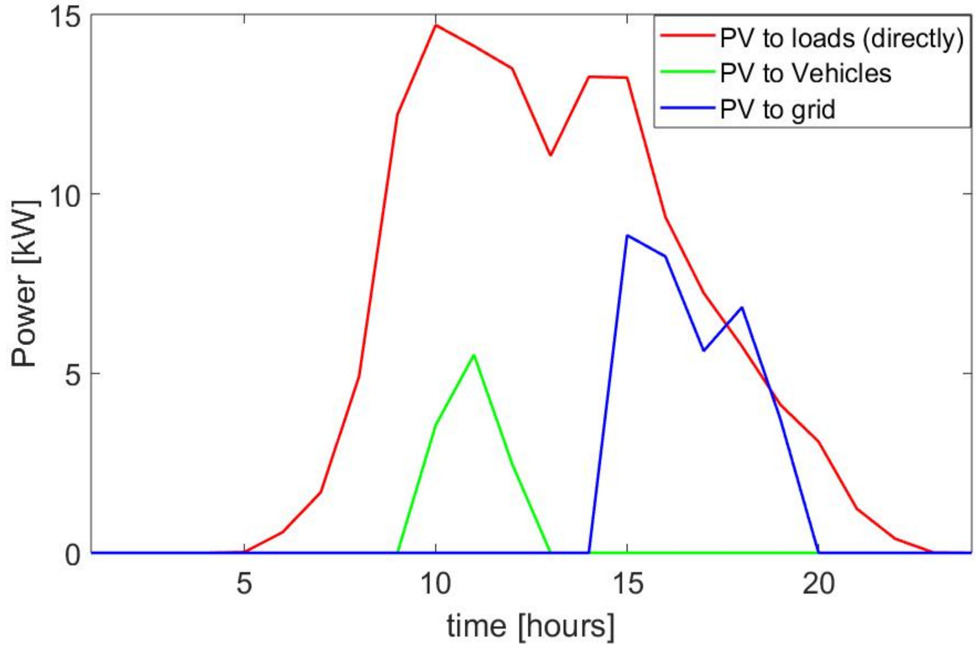

Figure 5.8: The usage of generated PV energy for 24 hours on a summer day

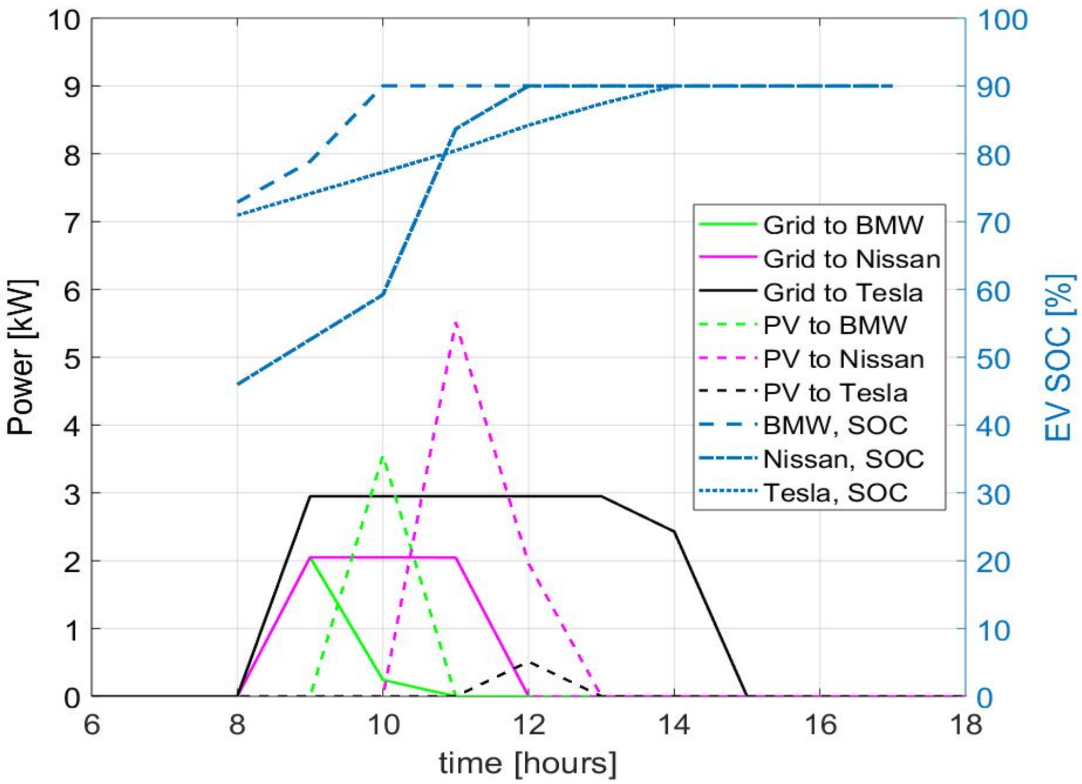

Figure 5.9: EV charging from PV energy & Grid on a typical normal working day. EV connected at 8a.m. and disconnected at 5p.m.

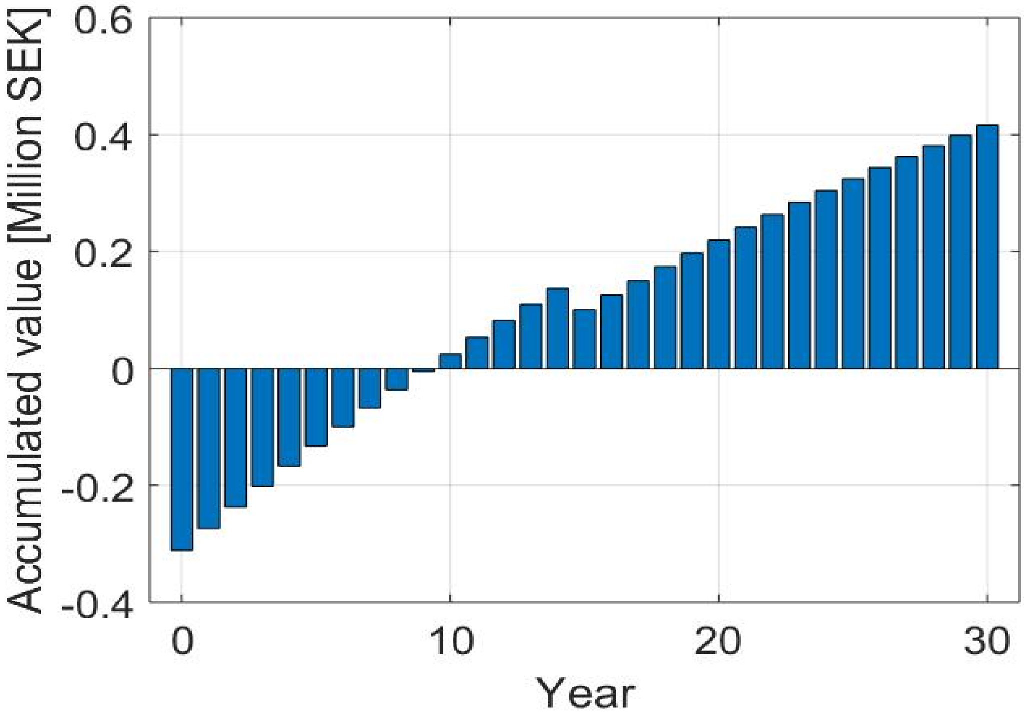

Figure 5.10: Nanogrid 5 payback period

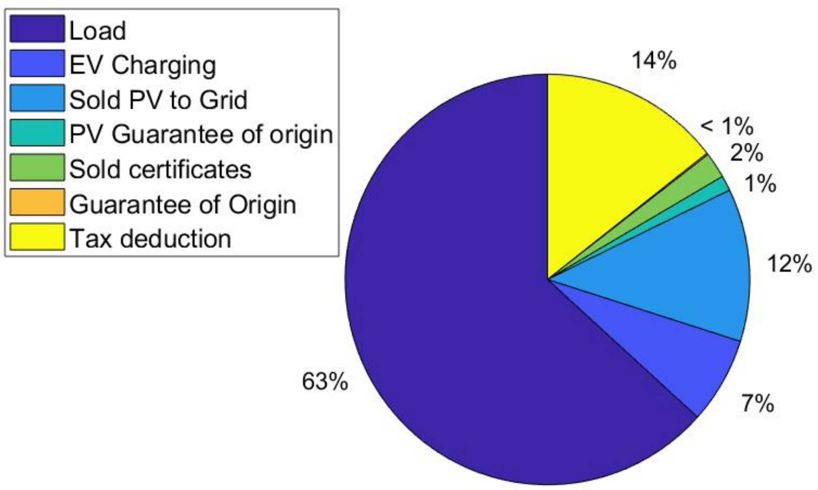

Figure 5.11: Nanogrid 5 PV energy income distribution

Table 5.2 shows a summary of results for all the nanogrids for the simulated year. The main aim of the thesis was to analyse how the values in table two are affected when the separate nanogrids are interconnected to form a microgrid that allows internal energy transactions.

Table 5.2: Performance of separate nanogrids

	Nanogrid 1	**Nanogrid 2**	**Nanogrid 3**	**Nanogrid 4**	**Nanogrid 5**
Energy from grid [kWh]	12,231	6,398	3,798	10,370	53,057
Total energy to loads [kWh]	18,666	12,641	8,355	14,805	59,247
Produced PV energy [kWh]	9,175	5,984	-	7,181	27,919
PV energy to grid [kWh]	5,218	3,322	-	2,543	9,010
PV energy to battery [kWh]	954	-	-	1,736	-
Grid energy to cars [kWh]	-	-	-	-	11,226
PV energy to Vehicle[kWh]	156	37.6	-	-	1,892
Vehicle to load energy [kWh]	2,757	3,732	4,701	-	-
PV energy used directly in system [kWh]	2,848	2,625	-	2,902	17,017
Self consumption (SC)[%]	42.5	44.5	-	63.1	61.0
Self sufficiency (SS)[%]	20.9	21.1	-	30.6	28.7
Annual Energy cost from grid [SEK]	17,223	8,957	5,317	-	-
Annual Energy cost from EV[SEK]	3,981	5,389	6,788	-	-
Total external energy cost [SEK/yr]	21,204	14,346	12,105	14,518	74,280
Pay-back period [years]	16	14	-	16	10

5.2 Scenario 2 (Microgrid)

5.2.1 Nanogrid 1

All the separate nanogrids were interconnected to form a microgrid. Instead of a nanogrid sending excess PV energy to the grid, the dispatch algorithm first checks to see if there is any other nanogrid in the microgrid that has a power deficit. If there is, the energy is sent to the nanogrid in need otherwise the excess is sold to the utility grid. Likewise, instead of importing energy from the grid whenever there is a power deficit, the dispatch algorithm checks for any nanogrid with an excess first before obtaining power from the grid. A 24 hour power flow plot for nanogrid 1 is shown in Figure 5.12 to highlight any differences with that of Figure 5.2 where there are no interconnections.

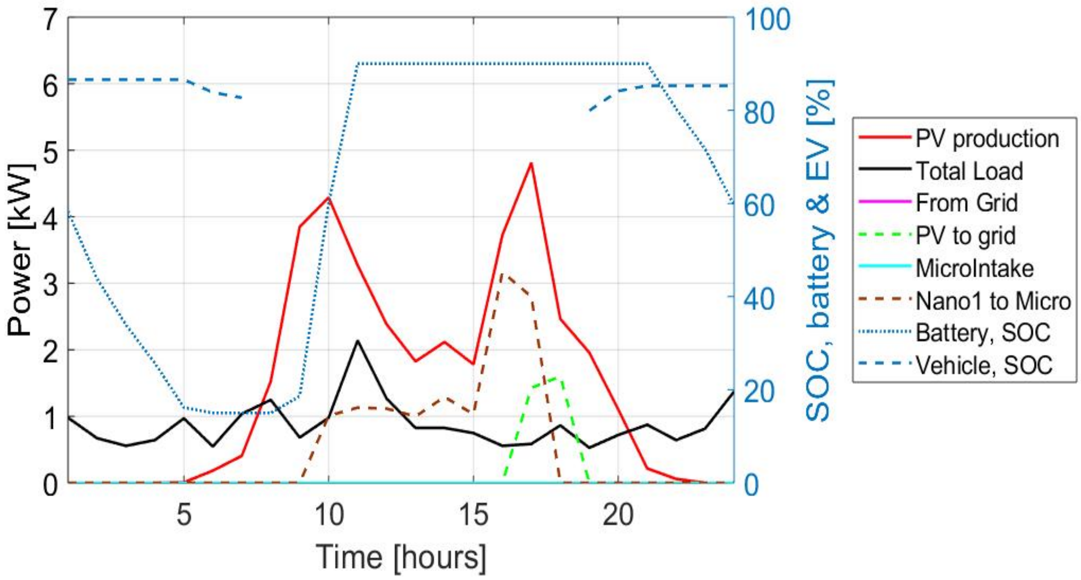

Figure 5.12: Nanogrid 1 flow of energy within the Microgrid on 20th June 2016

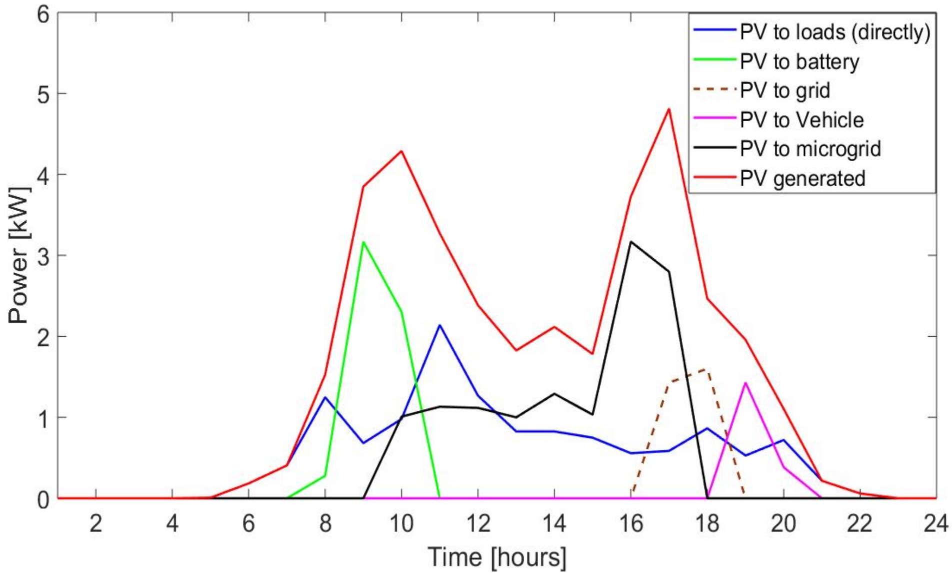

Figure 5.13: Nanogrid 1 usage of PV energy within the Microgrid on 20th June 2016

Figure 5.12 and Figure 5.13 show that on Tuesday 20 June 2018, nanogrid 1 did not obtain power with any other nanogrid since in Figure 5.2 and Figure 5.4, there was also no power intake from the utility grid. However, the nanogrid reduced its export to the utility grid by exporting excess power to other nanogrids as shown.

5.2.2 Nanogrid 5

The performance of nanogrid 5 was also plotted again on Monday 19th of June 2016 as before. Figure 5.14 shows the power of the office building in a microgrid. The solid black line in the figure shows that the nanogrid consumed energy from other nanogrids thereby reducing intake from the utility grid..

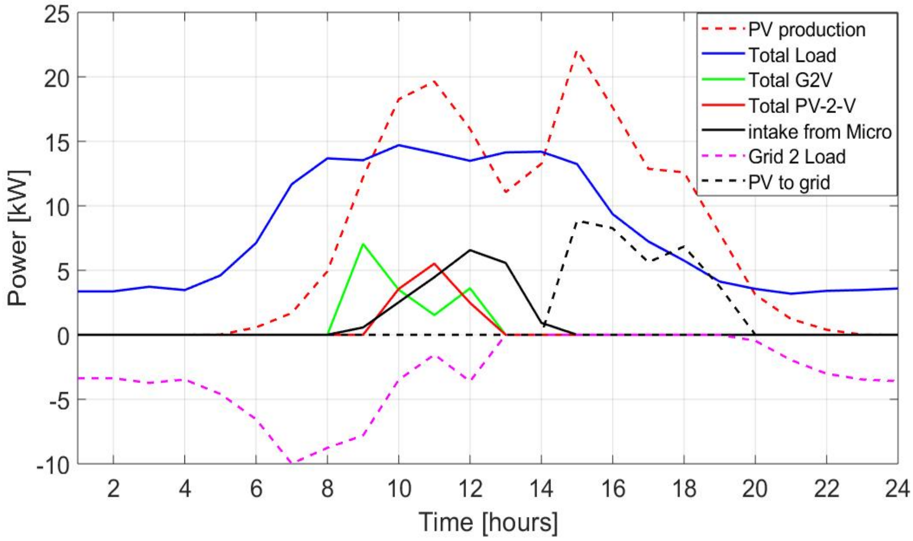

Figure 5.14: Nanogrid 5 energy flow within a Microgrid on a typical summer day

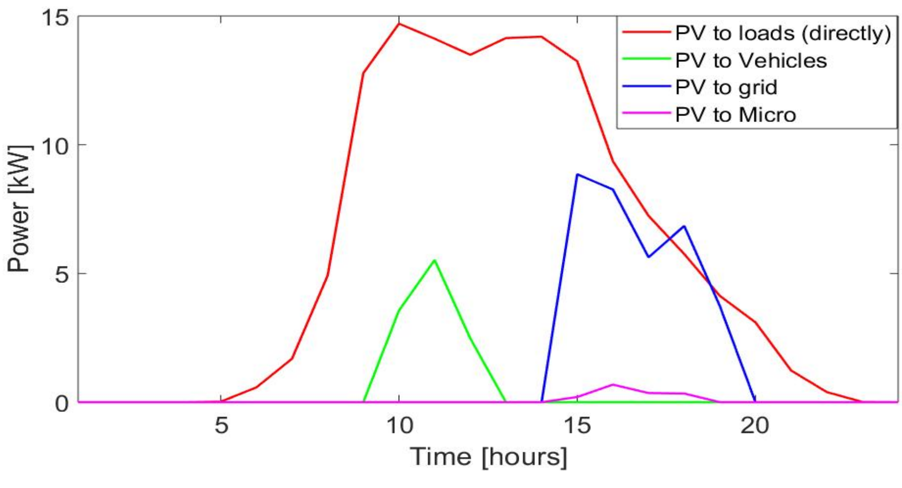

Figure 5.15: Nanogrid 5 PV energy usage within a Microgrid on a typical summer day

Figure 5.15 also shows that nanogrid 5 was pushing power to the other nanogrids. This clearly shows that power sharing between nanogrids was being realised thereby making the plots different from the grid connected plots in Figure 5.7 and Figure 5.8 respectively.

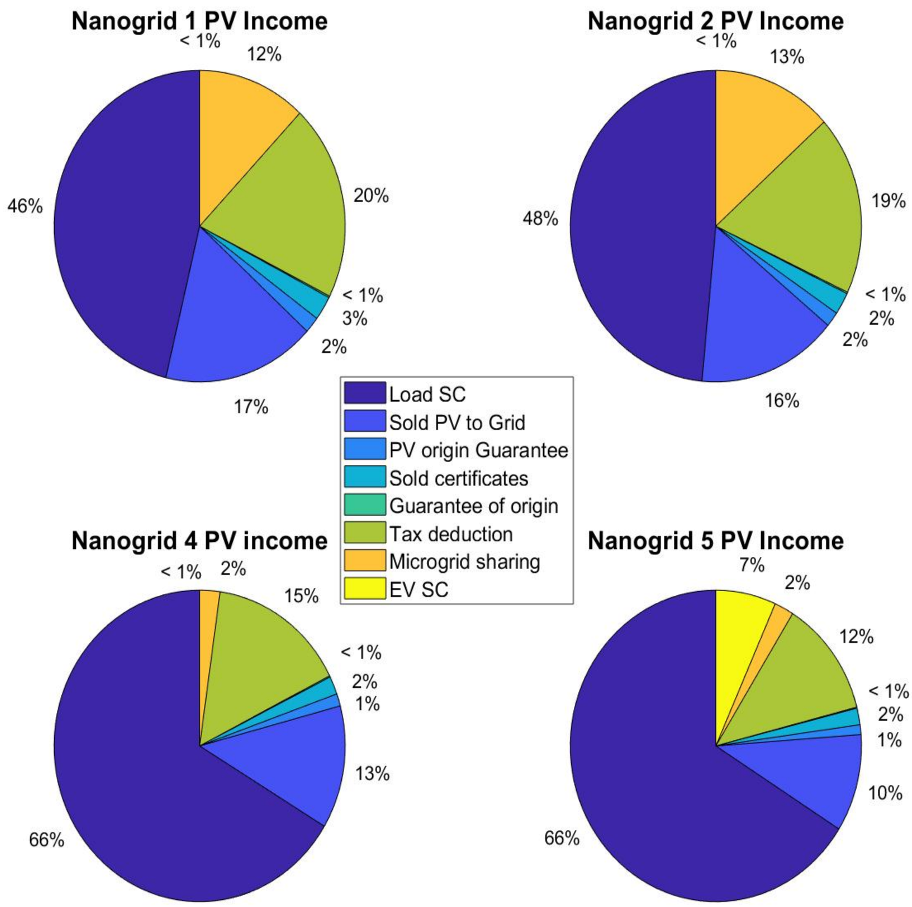

Figure 5.16: PV energy income of nanogrids within a microgrid

With the power sharing in place, financial contributions to the LCOE changes even though the payback period for all nanogrids remained the same. Figure 5.16 shows that the percentage of LCOE obtained from power sharing is very high for nanogrid 1 and 2. For both nanogrids, the money obtained from power sharing is the fourth highest after self-consumption cost, PV energy tax and sold power to the grid.

A summary of results for all the nanogrids interconnected to each other in a microgrid is shown in Table 5.3. Comparing with the results presented in Table 5.1 for the same nanogrids in grid connected mode with just a single external connection straight to the grid, it can be seen that the payback period is the same for all nanogrids. However, the annual total cost of all externally acquired energy by all nanogrids is reduced when interconnected as the proposed price for power sharing is less than grid energy buying price yet at the same time higher than the selling price to the utility grid. It is therefore advantageous to both parties in a transaction that is the seller and the buyer.

Table 5.3: Performance of nanogrids in a microgrid

	Nanogrid1	Nanogrid 2	Nanogrid 3	Nanogrid 4	Nanogrid 5
Energy from grid [kWh]	12,233	6,331	3,071	10,351	52,890
Total energy to loads [kWh]	18,666	12,641	8,355	14,805	59,247
Produced PV energy [kWh]	9,166	5,984	-	7,181	27,925
PV energy to grid [kWh]	4,025	2,452	-	2,371	8,314
PV energy to microgrid [kWh]	1,184	869	-	172	731
PV energy to battery [kWh]	954	-	-	1,736	-
PV energy to Vehicle[kWh]	155.6	37.6	-	-	1,804
Grid energy to cars [kWh]	-	-	-	-	11,229
Microgrid energy to nanogrid [kWh]	20.7	38.9	726.3	36.6	3,252
Vehicle to grid energy [kWh]	2789	3760	4701	-	-
PV energy used directly in system [kWh]	2885	2663	-	2920	17807
Self consumption (SC)	43.0	45.1	-	63.4	63.8
Self sufficiency (SS)	21.1	21.4	-	30.7	30.1
Annual Energy cost from vehicle [SEK]	3,908	5,358	6,663	-	3,501
Annual cost of external energy [SEK]	17,177	8,911	5,179	-	69,931
Annual total cost of external energy [SEK]	21,085	14,270	11,842	14,511	73,431
Pay-back period [years]	16	14	-	16	10

Since power obtained from another microgrid is treated similarly as power obtained from the utility grid when calculating SS and SC. The SC and SS of the nanogrids are the same for both scenarios except for nanogrid 5. Nanogrid 5 has a slightly higher SC and SS in the microgrid scenario because, in this study, electric vehicle charging energy was not considered as part of the internal load of nanogrid 5. Hence the interconnection of nanogrids resulted in a decrease in energy to the vehicle but increasing the local PV energy intake by the load as shown in the Table 5.3.

5.3 Comparison of Scenario 1 and 2

Checking the impact of power sharing on the individual performance of nanogrids did not show much differences in the payback period, SC and SS. However, the total cost of acquiring external energy per year was reduced. To determine the overall impact, all the grid connected nanogrids were combined to calculate the total energy being fed to the grid at each instance and also the total intake from the grid. For a clear visualisation, the plots for two summer days (Sunday 18 June and Monday 19 June 2016) are shown in Figure 5.17.

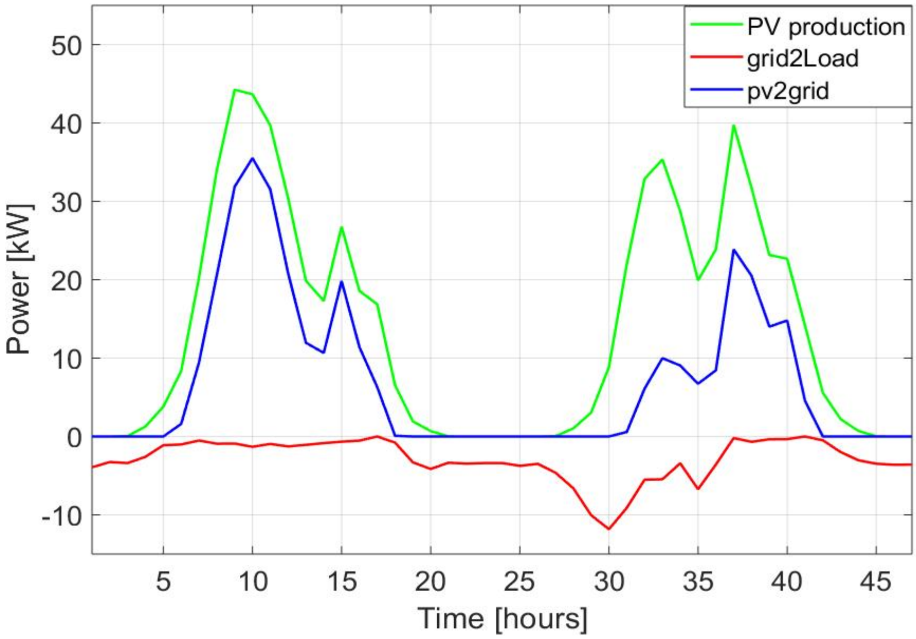

Figure 5.17: Power flow of Scenario 1 for Sunday 18 June and Monday 19 June 2016

Figure 5.17 shows the total solar PV energy production, energy imported from the grid and total energy exported to the grid for all the nanogrids. It can be seen that in some instances, the nanogrids are both consuming power to the grid and exporting power to the grid all at the same time. This phenomenon can be clearly seen from the 5th hour to the 15th hour and from the 30th hour to the 37th hour. It is this energy that we would like to channel for power sharing such that at any given point in time, it is either the system is importing or exporting but not both as it unnecessarily stresses the grid and increases conduction losses.

In the second scenario where there is power sharing between the nanogrids, the microgrid is either importing or exporting energy to the utility grid but not doing both at the same time as shown in Figure 5.18. The figures show that whenever the blue curve is not zero, the red curve is zero and vice versa except for the transition moments.

Table 5.4 shows a complete comparison of the two scenarios that were considered in this study. Table 5.4 shows that interconnection of the considered nanogrids to permit power sharing transactions reduced the grid intake by 1.2%. The PV energy exported to the grid was also reduced by 14.6%. The percentage is higher than that of grid intake because the initial PV energy to the grid (20,092 kWh) is much lesser than the initial energy import from the grid (85,925 kWh).

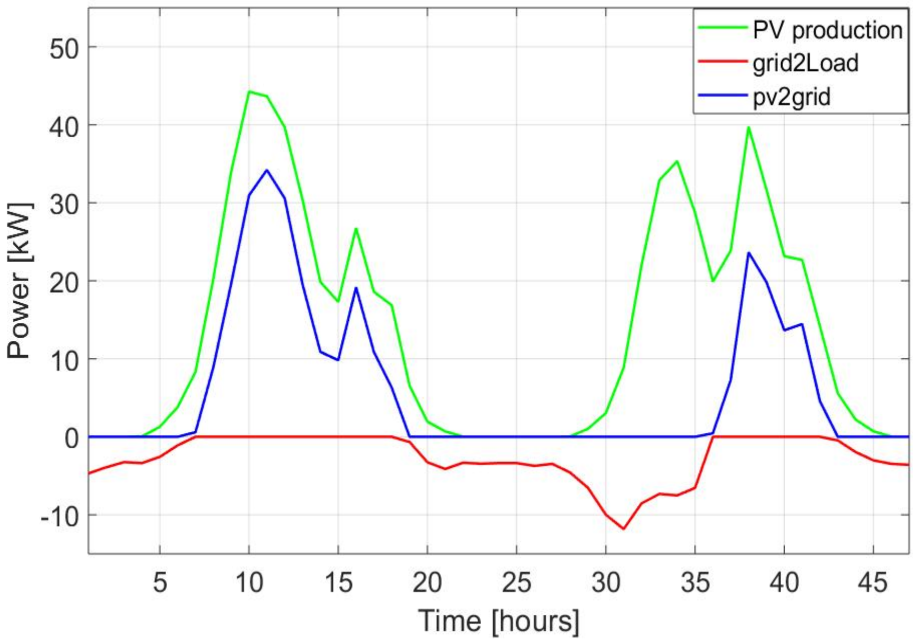

Figure 5.18: Power flow of Scenario 2 for Sunday 18 June and Monday 19 June 2016

Table 5.4: Overall performance comparison of scenario 1 and 2

	Scenario 1	Scenario 2	Percentage change
Energy from grid [kWh]	85925	84878	-1.2%
PV energy to grid [kWh]	20092	17163	-14.6%
PV energy to battery [kWh]	2,690	2,690	0.0%
PV energy5 energy to Vehicle [kWh]	2086	1997	-4.2%
Grid energy to Vehicle [kWh]	11226	11229	0.0%
Vehicle to load [kWh]	11190	11250	0.5%
Peak intake from the grid [kW]	40.8	40.8	0.0%
Peak PV energy export to Grid [kW]	50.4	49.8	-1.2%
PV energy used directly in system [kWh]	25,390	34,289	35.0%
Self consumption (SC) for PV energy[%]	59.6	80.5	20.9%
Self sufficiency (SS) for PV energy[%]	26.3	33.4	7.1%

The peak of the energy intake from the grid and export to the grid was obtained for both scenarios. Table 5.4 shows that there is no difference in peak intake, but the peak export was reduced by 1.2%. There is no difference for peak intake since this peak is realised during the winter where the load is generally high and there is not much production of PV energy hence any changes made to the PV energy system will not affect this value. However, there is a difference for the peak export because it occurs during the summer. However, the percentage change is not that big because the sizes of the PV energy installation had been optimized for grid connected operation hence when there is an excess, there will be an excess to all nanogrids except just nanogrid 3 which does not have PV energy installation. Considering that the household load is lower in summer and also during the day on a normal working day, the energy deficit of nanogrid 3 is small hence the small percentage difference.

As a result of limiting the interaction with the grid by allowing power sharing within the microgrid, the amount of PV energy used internally in the microgrid is increased significantly by 35.0%. This increase subsequently impacts the SC and SS which also increases by 20.9 percentage points and 7.1 percentage points respectively as shown in Table 5.3. In this study, the modelled microgrid has a self consumption of 80.5% whilst its self sufficiency is at 33.4%. This is a huge improvement as compared to the first scenario without power-sharing. However, to realise the full benefit of this setup, PV energy tax laws should be reviewed to accommodate microgrids. In this study, it was assumed, and the study proposes that the connecting fuse between the microgrid and the grid should not be limited to 100 amps as is the case for nanogrids but should be set at a value that accommodates all the nanogrids within a microgrid.

5.4 Sensitivity Analysis

A sensitivity analysis was carried out to evaluate the impact to the microgrid of varying nanogrid's parameters. The first variation was the doubling of installed PV for nanogrid 1 as shown in Table 5.5. If the owner of nanogrid 1 doubles the installed PV, the self consumption only increases by 0.7 percentage points whilst the self sufficiency only increases by 0.3 percentage points. This is as a result of a decrease in intake from EV and export to the utility grid. If another EV is added to the system that is nanogrid 2 owner purchases another Nissan Leaf, overall system intake from EV increases by 11.7%. However, SC and SS only increases by 0.3 and 0.1 percentage points respectively.

Supposing that the Tesla model S is removed from the system and nanogrid 3 can only either use power from the microgrid or the utility grid. The system intake from EV decreases whilst the energy import from the utility grid and the PV energy to grid increases. The SC and SS values are therefore reduced by 0.9 and 0.4 percentage points respectively. Reducing nanogrid 4's installed PV by half increases the self consumption by 3.4 percentage points whilst the self sufficiency is reduced by 1.1 percentage points. A drastic change is noted when nanogrid 5's load is doubled. Energy intake from grid increases by 61.1% and the SC also increases by 14.5 percentage points. However, the self sufficiency decreases by 6.9 percentage points. In the last case, nanogrid 5 PV is increased and the SC decreases by 12 percentage points whilst the SS increases by 2.9 percentage points.

Table 5.5: Microgrid's sensitivity as percentage change after parameter change

Microgrid percentage change from default value	Nanogrid 1: Doubled PV	Nanogrid 2: Doubled EV	Nanogrid 3: Remove EV	Nanogrid 4: Half PV	Nanogrid 5: Doubled Load	Nanogrid 5: PVx1.5
Energy from grid[%]	0.1	-1.2	2.2	1.4	61.1	-4.1
PV energy to grid [%]	-2.2	-0.9	2.7	-13.4	-42.3	60.7
Vehicle to Load [%]	-2.5	11.7	-41.8	0.0	-0.1	0.0
PV used directly in system [%]	-0.1	0.0	0.2	-2.1	25.5	7.6
Self consumption (SC) [%]	0.7	0.3	-0.9	3.4	14.5	-12.0
Self sufficiency (SS) [%]	0.3	0.1	-0.4	-1.1	-6.9	2.9

6
Discussion

6.1 Discussion of results

This study focused on up-scaling PV energy based nanogrids to form a microgrid with the aim of improving the overall PV energy self-consumption and self-sufficiency. It should be noted that the nanogrid parameters were not only limited to those with PV energy installation as there are some with just an electric vehicle (nanogrid 3). The current setup according to the Swedish regulations does not permit peer to peer energy transactions between nanogrids hence the nanogrids only directly interact with the grid whenever there is a deficit or an excess of PV energy. In this setup, if not for peak shaving, it is not financially beneficial to charge an EV from the grid to discharge to loads as there will be losses when charging and discharging. Rather than doing so, the loads can just get power from the grid directly. This is why in Table 5.1, the overall cost of externally acquired energy for a system without an electric vehicle was actually lower to that with an electric vehicle. However, in the second scenario, the electric vehicle can be charged from the cheap microgrid's internally shared energy thereby reducing the charging cost. If the system is well optimised, the amount saved from charging with internally shared energy can offset the charging and discharge losses of electric vehicles.

Payback period is not affected by all scenarios because the cost of battery has progressively been dropping and the subsidies that were introduced by the Swedish government greatly reduces the financial impact of incorporating a battery. In the past, the battery used to be an expensive part of the PV energy installation and had a huge impact on the payback period considering that it requires being changed just like the inverter.

For power sharing to occur, there is need to have at least one nanogrid with a power deficit and at least one nanogrid with an excess of power. However, in this study, nanogrids were initially optimised to operate on a grid connected basis. This means that in summer since it is assumed the nanogrids are in the same area and experiencing the same solar irradiance, all the nanogrids with PV panel installation would have excess PV energy leaving no nanogrid in need of excess power as was the case in Figure 5.12 and Figure 5.13. Furthermore, nanogrid 3 without PV installation would be the only nanogrid with a deficit but then the deficit is so small since all the load profiles took a dip in summer. The general load demand in summer is lower than in winter. In order to carry out a clear analysis of the impact of interconnecting nanogrids, there is need to interconnect a number of nanogrids with different designs and then optimizing the system for power sharing.

After carrying out a sensitivity analaysis as shown in Table 5.5, the impact to the microgrid system is more significant when changes are realised in nanogrid 5. This is so because nanogrid 5 has the highest load profile and unlike other nanogrids, nanogrid 5's daily peak value is realised during the day thereby coinciding with the PV energy daily peak.

6.2 Sustainable and ethical aspects

The energy produced from solar PV panel is indeed clean. However, some of the materials used to manufacture the solar panels are either toxic material or rare material. For instance, the cadmium telluride based solar cells where the cadmium is toxic and the telluride is hard to find. Cadmium telluride is known as the second generation in thin film solar cell technology. These solar cells are much better at absorbing solar radiation than the silicon-based solar panels.

Lithium-ion battery suggested in this project significantly improves the ability to more effectively use renewable energy resources. This leads to a new issue of their disposal when they complete the life cycle. Also, lithium ion batteries are at a risk of catching fire. So, it is not possible to dispose them anyhow and forget about it. It is important to find a special way of recycling lithium-ion batteries and much research on that is currently underway.

7
Conclusion

The simulation results show that the interconnection of nanogrids to form a microgrid improves the overall self-consumption and the self-sufficiency significantly. In this study, the SC and SS were increased by 20.3 percentage points and 6.9 percentage points respectively even though the system was not optimized for power sharing.

The peak energy import from the grid can be reduced by implementing power sharing between the nanogrids, especially in the summer if the system is such that there are nanogrids without or with undersized PV systems. Also, the peak of exported energy to the grid is also reduced since unlike the system with standalone nanogrids, at any given point in time, the system would be taking power from the grid or sending power to the grid but not doing both at the same time.

Neglecting the cost of interconnecting the nanogrids (such as cables, controlling software etc), the financial benefit is not that huge as per the obtained results. However, a well-optimized system for power-sharing with predictive capabilities can significantly improve the financial benefits of upscaling local DC nanogrids to block level interaction within a microgrid.

Finally, the Swedish electricity market has a strong market structure that works fine. However, in the future the main energy production types may change and become more distributed. As a result of the change, the electricity market may also require some changes. The electricity market in microgrids is a new concept that does not have many examples. Peer to peer trading system for microgrid such as blockchain technology is still in the development stage. It will take time to fully develop and implement the technology.

Since this study is at a very beginning stage, it is hard to predict economic perspective. In this study, some ongoing projects of blockchain application in the microgrid are presented. However, it would require more studies to make a well-informed assessment. To conclude, the future electricity market will most likely head in this direction of the decentralised payment system such as blockchain hence, the up-scaling of DC nanogrids is indeed a lucrative venture which still require more research.

7.1 Future work

1. Incorporating a dispatch algorithm that has predictive capabilities to minimise intake of grid energy to charge electric vehicles.
2. Analysing an improved number of nanogrids and optimising the sizes of the PV installation and energy storage systems for power sharing.
3. Incorporating the cost of interconnecting cables, the controlling mechanism and the block chain energy management system when determining the financial benefits of implementing up scaling to block level interaction.
4. Analysing the possibility of adding a wind turbine to the microgrid and effectively produce power even in winter along with the solar PV.
5. Study the possibility of using other energy storage systems that can store energy for longer periods to cover the winter period for example electrolysis of water.

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A

Appendix 1

Figure A.1 shows the battery data sheet of the installed battery at RISE's research villa in Borås. Figure A.2 shows the battery capacity of different electric cars and their respective charging limits and energy consumption as measured in the year 2017.

ferroamp

ESM7 – Energy Storage Module

	ESM7 – Energy Storage Module
Battery	**7.2 kWh**
Battery capacity, Q_{NOM}	12 Ah
Battery voltage, V_{NOM}	614 V
Maximum charge voltage, V_{MAX}	690 V
Minimum discharge voltage, V_{MIN}	422 V
Maximum continuous battery current, I_{BAT}	+/- 10 A
Battery fusing	2 x 10 A, 1000 VDC fuse link 10x38 mm
Battery connection	Hirose DF22
Battery electrical roundtrip efficiency	94% (0.5 C)
Maximum battery potential to ground	1 kV_{RMS}
Physical	
Dimensions W x H x D	482 x 178 x 980 mm
Weight	88 kg
Color	Black
Installation	
Ambient temperature [1)]	-10°C – 45°C
Humidity	0 – 95% RH non-condensing
Degree of protection	IP 21
Cooling	Forced air cooling with temperature controlled fan
External power supply	5 V (BMS), 12 V (Interlock chain)
BMS	
Communication	CAN bus, USB
Protection functions	Cell overvoltage, undervoltage, overtemperature, output short circuit, polarity reversal, external interlock
BMS functions	Predictive cell balancing, State-of-charge estimation, State-of-Health estimation, cell voltage measurement, total voltage and current measurements, total energy measurements
Compliance	
LVD	IEC 62477-1
EMC	EN 61000-6-2, EN 61000-6-3
Battery safety	IEC 62619, UN 38.3

1) Power may be derated if ambient temperature is outside the range 0 - 40 °C
2) Items included in delivery are 1 x BMS front, 4 x 150 V battery modules, 1 x rack shelf

Större energilager hos kund

Vänster kabinett
2 st EnergyHub XL 28 = 56 kW effekt.

Höger kabinett
7 x ESM 7,2 med 7 x ESO 6; Totalt 50,4 kWh/42 kW

CE Ferroamp Elektronik AB, Domnarvsgatan 16, 163 53 Spånga, Sweden - www.ferroamp.se – +46 8 684 333 90

Figure A.1: RISE research villa installed battery data sheet

Manufacturer	Name	EV/PHEV	Battery Chemistry	Capacity [kWh]	E Engine P [kW]	Vehicle Weight [kg]	B Pack share in weight [%]	Sp. Range [km/kWh]	E. Rang [km]
Tesla	Tesla Model S 75D	EV	NCA	75	245	2108	24	6	405
	Tesla Model S 90D	EV	NCA	90	311	2240	25	5.5	445
	Tesla Model S 100D	EV	NCA	102	451	2390	25	5.5	510
	Tesla Model S P100D	EV	NCA	102	567	2234	26	5.5	505
Toyota	Toyota Prius Prime	PHEV	NMC	8.8	20	1526	7	5.5	40
General Motors	Chevrolet Bolt EV	EV	NMC	60	149	1624	27	7	350
	Chevrolet Volt	PHEV	NMC	18.4	111	1607	11	5.5	85
Volkswagen	VW e-Golf	EV	NMC	35.8	100	1605	22	6.5	195
	VW e-up	EV	NMC	18.7	60	1139	20	7	110
	VW Golf GTE	PHEV	NMC	8.8	75	1520	8	6	45
	VW Passat GTE	PHEV	NMC	9.9	85	1722	8	5.5	45
Audi	Audi A3 Sportback e-tron	PHEV	NMC	8.8	76	1654	7	5	35
	Audi Q7 e-tron	PHEV	NMC	17.3	94	2445	9	4	55
Porsche	Porsche Cayenne S E-Hybrid	PHEV	NMC	10.8	71	2360	6	4	35
	Porsche Panamera 4 E-Hybrid	PHEV	NMC	9.4	100	2170	6	5	40
Nissan	Nissan Leaf	EV	NMC	30	80	1516	20	7	170
Hyundai	Hyundai Ioniq Plug-in	PHEV	NMC	8.9	45	1370	9	6.5	50
	Hyundai Ioniq Electric	EV	NMC	28	88	1420	20	7	165
Ford	Ford Focus Electric	EV	NMC	33.5	107	1651	20	6.5	180
	Ford C-Max Energi	PHEV	NMC	7.6	88	1769	6	5	30
Fiat	Fiat 500e	EV	NMC	24	83	1352	19	7	135
BMW	BMW i3	EV	NMC	33	127	1343	24	6.5	180
Daimler	Mercedes-Benz B-class E Drive	EV	NCA	36	132	1725	17	6	165
	Smart Fortwo Electric Drive	EV	NMC	18	60	995	16	7	120
Kia	Kia Soul EV	EV	NMC	27	82	1554	18	6.5	145
Renault	Renault Zoe	EV	NMC	41	68	1480	26	7	230
Karma	Karma Revero	PHEV	NMC	21.4	106	2450	10	4.5	80
BYD	BYD E6	EV	LFP	82	89	2420	29	5	390
Mitsubishi	Mitsubishi i-MiEV	EV	NMC	16	49	1170	19	7	95
	Mitsubishi Outlander	PHEV	NMC	12	119	1845	10	5	45

Figure A.2: Battery Capacity of EV and their respective charging limits and energy consumption as measured in 2017 [62]