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TAMPERE UNIVERSITY OF TECHNOLOGY

JUHA MAJURI

PHOTOVOLTAIC SYSTEM WITH BATTERY ENERGY STORAGE IN FINNISH RESIDENTIAL USE

Master of Science thesis

Examiner: lecturer Risto Mikkonen
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ABSTRACT

JUHA MAJURI: Photovoltaic System with Battery Energy Storage in Finnish Residential Use
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This thesis discusses the use of battery energy storages (BES) with photovoltaic (PV) systems and, in particular, their use in domestic residences in Finland. The main objective is to determine which battery technology is the most promising to add to Naps Solar Systems' product portfolio for home battery energy storage. The benefits of using the chosen product in parallel with photovoltaic systems is analyzed. The cost savings and other benefits for residential customers are thoroughly analyzed with simulations.

The thesis discusses the theory behind photovoltaic cells, and describes their current rate of market penetration. It presents a techno-economic comparison of the three most commonly used battery technologies, i.e. the lead-acid, lithium-ion and nickel batteries. Although the study focuses on battery energy storage for residential, grid-connected customers, it also gives an overview of other energy storage technologies. It examines possible topologies, control systems and the benefits to be gained from battery energy storages, particularly with regard to their profitability.

The thesis concludes that battery energy storage based on lithium iron phosphate seems to be the optimal solution for residential PV use. Lithium iron phosphate is one of the safest lithium ion battery technologies, and its cycle lifetime is by far the longest. Therefore, simulations were performed using lithium iron phosphate batteries with capacities ranging from 4-16 kWh. Differently-sized PV systems affect the profitability and operation of a BES system, and these effects are reviewed, as is the impact of having an electric heating system.

At the moment, battery energy storage is not a particularly profitable investment. However, most PV+BES systems will reach payback in their lifetime, and they do have a positive net present value. In Finland, the possibility of time-of-use-shifting, coupled with high differences in the spot market price, does indicate some future potential for battery energy storage. At present, these systems are more likely to be bought for ecological rather than economic reasons, and these factors are also considered when recommending the product for Naps Solar Systems.

TIIVISTELMÄ

JUHA MAJURI: Akkujärjestelmät aurinkosähköjärjestelmän tukena suomalaisissa asuintaloissa
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Tämä diplomityö tarkastelee verkkoon kytkettyjen akkujärjestelmien kannattavuutta ja toimintaa aurinkosähköjärjestelmien tukena suomalaisissa asuintaloissa. Työn pääasiallisena tarkoituksena on valita Naps Solar Systemsille uusi tuote (kotiakkujärjestelmä) yrityksen tuoteportfolioon. Valitun tuotteen kannattavuuteen ja toimintaan perehdytään simulaatioiden avulla.

Työn alussa käsitellään aurinkosähköjärjestelmien teoriaa, ja Suomen ja globaalin aurinkosähkömarkkinan tilanne analysoidaan. Kolmannessa luvussa käydään läpi akkuteknologian perusta sekä tarkastellaan kolme yleisimmin käytettyä akkuteknologiaa: lyijy-, litiumioni- ja nikkeliakku. Teknistaloudellinen vertailu tehdään näiden eri teknologioiden välillä. Luvun lopussa tehdään katsaus muista energian varastointiteknologioista. Sen jälkeen käydään läpi mitä verkkoon kytketyt akkujärjestelmät ovat, ja mitkä ovat topologiavaihtoehdot, miten järjestelmiä ohjataan ja mitkä ovat järjestelmien hyödyt.

Akkujärjestelmä, joka perustuu litiumrautafosfaattikennoihin, on työn tuloksena suositeltava akkuteknologia aurinkosähköjärjestelmien tukena käytettäväksi. Litiumrautafosfaatti on yksi turvallisimmista litiumioni-teknologioista ja sen sykli-ikä on myös hyvin korkea. Tuote joka perustuu aiemmin mainittuun litiumrautafosfaattiin, valitaan Naps Solar Systemsin tuotevalikoimaan. Simulaatiot tehdään tämän tuotteen pohjalta. Valitun tuotteen kapasiteetti voidaan valita 4-16 kWh väliltä 2 kWh välein. Simulaatioiden pohjalta tehdään suositukset miten eri kokoiset aurinkosähköjärjestelmät vaikuttavat akkujärjestelmän kokoon. Simulaatioissa tarkastellaan myös sitä, miten sähkölämmitys vaikuttaa akkujärjestelmän toimintaan.

Tällä hetkellä akkujärjestelmät eivät ole kannattavimpia investointikohteita. Kuitenkin, aurinkosähkö- ja akkujärjestelmä yhdessä tuottavat positiivisen nettonykyarvon ja maksavat elinaikanaan itsensä takaisin. Järjestelmien kannattavuus voi kuitenkin parantua merkittävästi järjestelmien hinnan laskiessa, sähkön hintojen noustessa, sekä mahdollisten tukijärjestelmien käytäntöön tulossa. Mahdollisuus käytön aikasiirtoon (TOU-shifting) ja spot-hintojen suuret vaihtelut tekevät Suomesta potentiaalisesti paremman markkinakohteen. Tällä hetkellä järjestelmiä myydään kuitenkin pääasiassa enemmän ekologieselta kuin taloudelliselta näkökantilta, joka on otettu myös huomioon valitessa tuotetta Naps Solar Systemsille.

PREFACE

It has been such a pleasure working in Naps Solar Systems, making this Master's Thesis and diving into the photovoltaic and battery industry for real. First, I would like to express my gratitude to D.Sc. Mikko Juntunen, CTO of Naps Solar Systems, who, having put his faith in me by giving me the chance to do this Master's Thesis, went on to guide me throughout the whole process. His experience and knowledge of photovoltaic technology has been invaluable to me. I would also like to thank Dr. David Spiers for his technical proofreading of the thesis and his valuable advice. Despite having already retired from Naps, he was ready to invest his time in this work. Thank you very much! I would also like to thank all of my colleagues at Naps Solar Systems who have warmly welcomed me into their work community, so special thanks to all of you who have helped me along the way. I hope I can continue working alongside everyone at Naps in the future.

Then, I would like to thank my examiner and instructor at Tampere University of Technology, Lecturer Risto Mikkonen. He guided me through my Bachelor's Thesis, so I was delighted to be under his instruction for my Master's Thesis. He has given much good advice, which has helped me to focus on the important aspects of this work. I would also like thank Adrian Benfield for his proofreading of my English.

Thank you also to all my friends and family, who have helped me to relax and escape from my studies and work. Thank you for all the game nights and other social occasions, which have meant so much to me.

Next I like to thank my parents in Finnish: Suurimmat kiitokset menevät vanhemmilleni, jotka ovat pienestä pitäen aina näihin päiviin saakka tukeneet minua kaikin mahdollisin keinoin. En olisi nyt valmistumassa diplomi-insinööriksi ilman heitä ja heidän tukeaan. Olette parhaat vanhemmat, joita poika voi toivoa itselleen!

Finally, I reserve my greatest gratitude to Pirita for her unwavering support and love throughout my time at university, and even before that. Six years is a long time but I still feel that we are only beginning our journey together. It is so wonderful to be marrying you next summer! You are my best friend and it is such a privilege to have you by my side. I love you!

Tampere, 12.5.2017

Juha Majuri

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

PV	photovoltaic
BES	battery energy storage
BESS	battery energy storage system
BOS	balance of system
AM	air mass
SMES	superconducting magnetic energy storage
CAES	compressed air energy storage
UPS	uninterrupted power supply
TOU	time of use
Li-ion	lithium-ion
Pb-acid	lead acid
$LiFePO_4$	lithium iron phosphate
NMC	lithium nickel manganese cobalt oxide

G	solar irradiance
P	power
V	voltage
I	current
E	energy
η	efficiency
A	surface
t_h	utilization period of maximum load
C_0	investment costs
C_t	net cash flow of year
r	discount rate

1. INTRODUCTION

The general public's increasing awareness of the effects of climate change has given rise to political initiatives such as the Paris Climate Agreement [1] and to an urgent demand for clean and renewable energy. These factors, allied with the reduced costs of renewables, have led to the increased market penetration of distributed energy resources such as photovoltaic (PV) systems. However, one of the main problems with PV systems is that the electricity production is, by its very nature, intermittent. At night, there is no solar irradiance, so any type of PV electricity generation system needs to cope with this. The problem is further complicated by the fact that in most households the demand for electricity is lowest during the day, when PV generators achieve peak production. The solution is to store the surplus energy produced during daylight hours in a battery energy storage (BES) system, so that the stored power can later be used when the demand for electricity in domestic households is at its peak.

The purpose of this research is to evaluate the benefits of using battery energy storage systems in parallel with a grid-connected photovoltaic system in a typical Finnish household. Specifically, the cost benefits for differently sized and operated systems will be calculated with simulations. The study also presents a brief overview of the various battery energy storage technologies available, and makes a techno-economic comparison of them.

This study has been commissioned by Naps Solar Systems. Naps is the most experienced solar electricity company in Finland and one of the most experienced companies globally. Naps was established by Neste in the early 1980s, when it started research into alternative energy technologies. Since then, Naps has delivered more than 200 000 solar electricity systems to over 140 countries on all continents, including Antarctica. Naps became an independent company in the year 2004.[2] In addition to its expertise in photovoltaic systems, the company also has long experience and know-how in the use of batteries and control electronics. Naps has installed many off-grid systems with BES, but grid-connected battery energy storages are a new thing on the market. One of the main purposes of this research is to recommend what kind of battery energy storage system the company should include in its product portfolio. This involves investigating the operation, sizing and installation of home BES systems in Finland.

Photovoltaic systems, including the operation of solar cells, are introduced in Chapter 2. This chapter also reviews the state of the solar energy market in general, and examines the effects of various operating conditions. Chapter 3 reviews the different battery technologies and presents a techno-economic comparison of them. The decision about the optimal battery technology is made based on this analysis, although alternative energy storage technologies are reviewed at the end of the chapter. The next chapter describes the basic principles of battery energy storage, and introduces different system topologies. Aspects affecting the profitability of PV and BES systems are reviewed in Chapter 5.

The recommendation for a grid-connected battery energy storage system for Naps Solar Systems is based on the information and technical data presented in the first five chapters. The final part of the thesis aims to make a case study of the chosen PV-BES system, highlighting its benefits for the typical Finnish domestic consumer. The particular household used in the study already has a 1.5 kW_p PV system installed. A number of simulations are conducted in order to evaluate the profitability of the PV-BES system under different operating conditions. The profitability of the BES is compared using three different PV systems (3.5, 7 and 10.7 $kW_{p)}$. Simulations are also performed with other consumption data in order to give some insight into how electric heating affects the operation and profitability of the battery energy storage system.

2. PHOTOVOLTAIC SYSTEMS

Every hour enough solar energy arrives on Earth to satisfy the global electricity demand for one year. If we could harness only a small portion of this energy, it would provide enough power for the whole of mankind. With photovoltaic modules operating at 10 % efficiency, we would need approximately 0.4 % of the Earth's surface to satisfy the total global energy demand, which is less than is currently used for agriculture.[3]

Solar energy can be converted directly into electricity with photovoltaic modules through a phenomenon called the photovoltaic effect. Solar energy can also be collected as heat with solar heat collectors. This heat can then be used for heating residences, or water, or it can also be converted into electricity indirectly with a steam turbine (concentrating solar heat collector). This thesis only discusses solar systems operating with photovoltaic modules.

Edmond Becquerel discovered the first photovoltaic device in 1839. However, the theory behind this phenomenon and its complete effects were not fully understood until the development of quantum mechanics and semiconductor technology in the 20th century. [4]

The advantages of photovoltaic systems are outlined in [3] and summarized below:

- Fuel is present almost everywhere and it is infinite
- Pollution- and radiation-free
- Low operation and maintenance costs
- No moving parts and almost maintenance-free
- Reliable; manufacturers guarantee 25-30 years of operation with at least 80 % of energy yield
- Annual energy yield is predictable
- Modular; can be used in both small and large applications
- Can be easily integrated into both new and existing infrastructures
- Quick installation.

The main disadvantage of photovoltaic systems [3] are:

- The systems are (or used to be) regarded as expensive
- Hourly and daily electricity generation is intermittent and unpredictable
- Generation does not always match demand
- The systems are quite large

As Figure 1 (below) shows, the costs of solar modules are decreasing all the time. Ten years ago, the bulk of the cost of a PV system (70%) came from the solar modules, but their price has dropped, and nowadays nearly half of the cost of the system comes from the cost of the inverter and other Balance of System- (BOS) related devices (Figure 1).

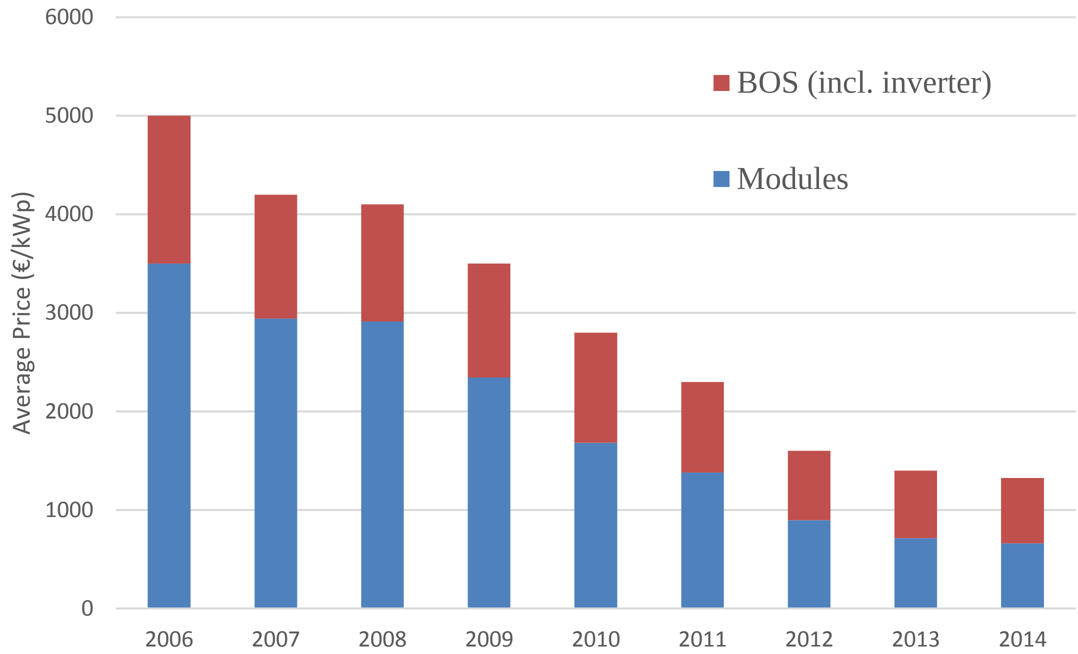

Figure 1. *Decrease of investment cost of PV modules and system (installed on the roof with the size of 10-100 kW in Germany). Adapted from [5].*

Photovoltaic systems are fast approaching the point at which they can compete against any other means of energy production in terms of cost. Therefore, this chapter will present an overview of the current state of photovoltaic technology, including the effects of different operating conditions, the inclination of the solar modules, and its BOS. The chapter concludes with an overview of the current state of the photovoltaic market and industry in Finland.

2.1 Solar irradiance

Any solar irradiance that reaches Earth arises from nuclear reactions within the Sun. The Sun emits high intensity radiation from its surface with a power of 3.8 x 10^{26} W. Ultimately, only 0.000000045% of that radiation reaches the Earth's atmosphere. Nevertheless, this is equivalent to 1.7 x 10^{17} W.[6] Solar radiation is usually measured by the power per unit area that the incoming radiation inflicts on a plane. This measurement is referred to as irradiance, *G*. The irradiance reaching the outer edge of Earth's atmosphere is approximately 1368 W/m^2 [6]. This so-called 'solar constant' is divided into: 8 % in the ultraviolet range, 47 % in the visible light range, and 45 % in the infrared range. The solar constant is dependent on solar activity and the Earth's elliptical orbit around the Sun, so it is not actually constant, and can vary by ± 3.5%. [6]

Only 49 % of the energy reaching the top of the atmosphere penetrates to the surface of the Earth. The rest is either reflected back into space or absorbed in the Earth's upper atmosphere. For example, clouds can block the incoming rays and reduce the amount of irradiance reaching the Earth's surface by 80-90 %. The difference between solar irradiance on a clear sunny day and on a cloudy day is graphically illustrated in Figure 2.

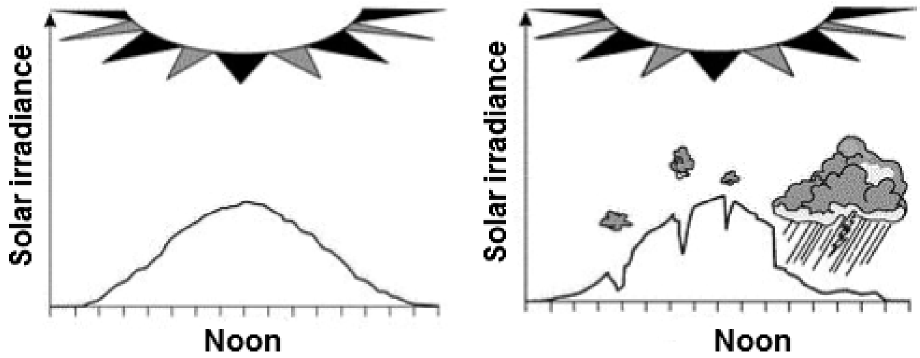

Figure 2. *Solar irradiance on sunny day vs. cloudy day. Adapted from[7].*

Air mass (AM) represents the effects of a cloudless atmosphere on solar irradiance and its spectrum. Air mass is defined as a division of the length of the irradiance travelling across the atmosphere and the thickness of the atmosphere, i.e.

$$AM = \frac{l_{irradiance\ at\ the\ atmosphere}}{l_{atmosphere}} = \frac{l_{irradiance\ at\ the\ atmosphere}}{l_{irradiance\ at\ the\ atmosphere}\cos\theta} = \frac{1}{\cos\theta} \qquad (2.1)$$

where θ is angle of incidence of the solar irradiance. Figure 3 illustrates the variables affecting air mass, and also presents some air mass values.

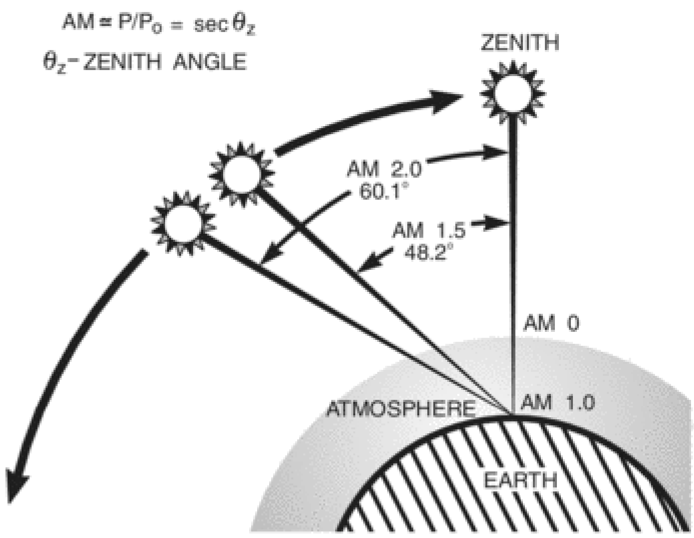

Figure 3. *Air mass [8].*

Air mass is 1 at the Earth's surface when the sun is at its zenith and the air mass is 0 at the top of the atmosphere. Air mass affects the intensity and the spectrum of the solar irradiance reaching the Earth, because the molecules in the atmosphere scatter and reflect the radiation. The most important air mass value is 1.5, which is used as the standard test condition for solar cells. With an AM of 1.5, the zenith angle is $\theta = 48.2^0$. [8]

Solar rays can hit the ground directly, or indirectly after being reflected or scattered by the atmosphere or by objects on the ground. Indirect irradiance is often called diffuse radiation. The combination of both direct and diffuse irradiance is the base source of photovoltaic solar energy generation. The solar spectrum in the atmosphere and on the surface of the Earth is illustrated in Figure 4. Here, the air mass is AM1.5, and the figure also shows the differences between direct and diffuse radiation.

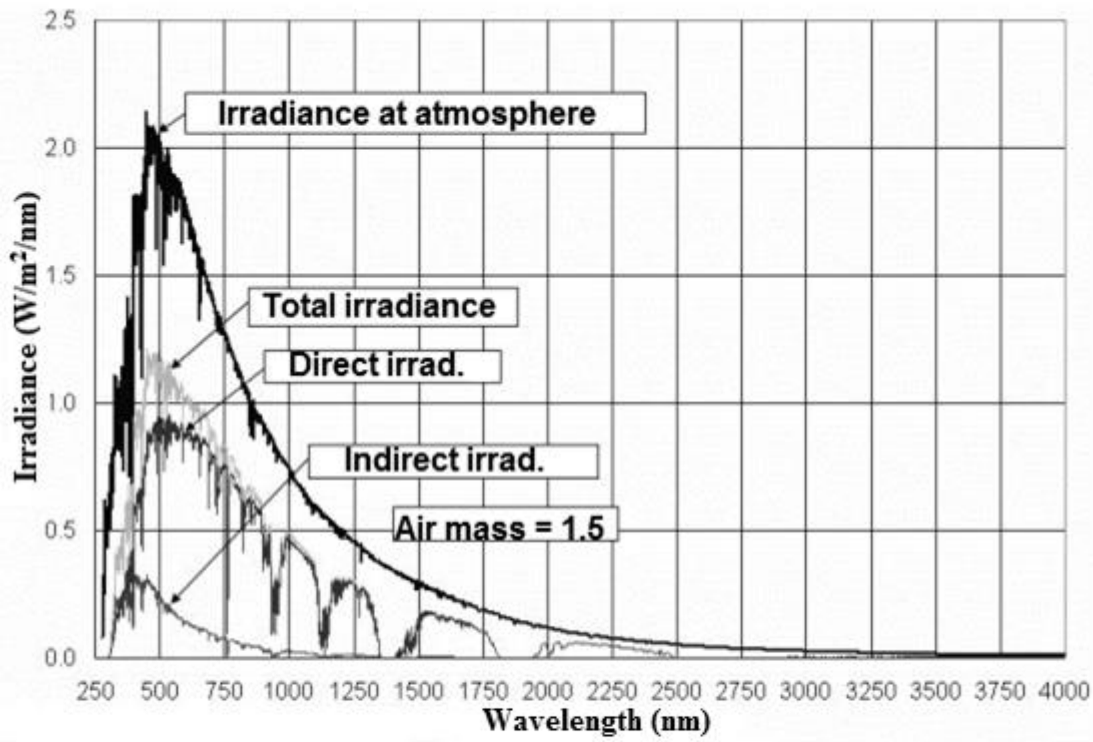

Figure 4. *Differences in the solar spectrum between the atmosphere and the Earth's surface. Adapted from [7].*

As Fig. 4 shows, much of the irradiance is lost in the atmosphere. It should also be noted that at certain wavelengths, almost all of the radiation is absorbed because some molecules which are abundant in the atmosphere absorb a greater part of the solar energy at these wavelengths.

2.2 Overview of PV Technology

The most common solar cells used in solar modules are based on monocrystalline or polycrystalline silicon. Other types of solar cells have been developed, such as cadmium telluride (CdTe), amorphous silicon and copper indium diselenide (CIS) cells. However, this thesis will confine itself to a discussion of solar cells based on monocrystalline or polycrystalline silicon. Solar cells are devices which transform solar irradiation into electricity. They are semiconductors, usually 156 x 156 mm in size, and they generate a voltage of 0.5-0.6 V. A typical PV cell with all its components is illustrated in Figure 5.

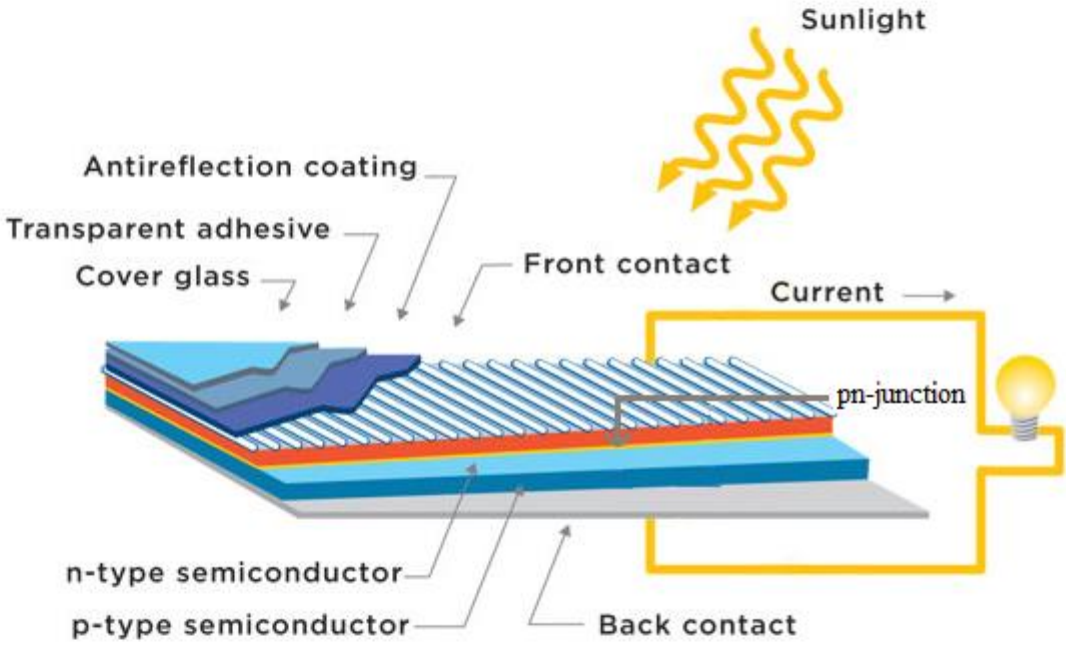

Figure 5. *PV cell and components. Adapted from [9].*

A solar cell includes a pn-junction, front and rear current collectors and anti-reflection coating. The principle behind the cell's operation is quite straightforward. When a load is attached to the cell and solar irradiance hits it, electrons starts to flow, which produces an electric current. Detailed operation of a solar cell is explained in section 2.2.1

Figure 6 shows two silicon-based solar cells. The one on the left is a poly-crystalline solar cell, and the one on the right is mono-crystalline. Mono-crystalline silicon has an ordered crystal structure. It is manufactured from one silicon crystal and grown to the required cell size. This slow and painstaking manufacturing process makes it more expensive than the polycrystalline cell [4] so polycrystalline cells are being used more and more by the industry, despite the fact that their overall performance might not be quite as good as that of a monocrystalline one. The great advantage of polycrystalline cells is that they are easier, and cheaper, to manufacture. The main drawback with polycrystalline solar cell is that they include different regions of crystalline silicon separated by grain boundaries. These boundaries make the bonding between the crystal structures irregular and reduce the cell's performance by blocking carrier flows. They also increase other losses in the solar cell. However, according to [4] significant losses at the grain boundaries can be avoided if the grain sizes can be limited to the order of a few millimeters.

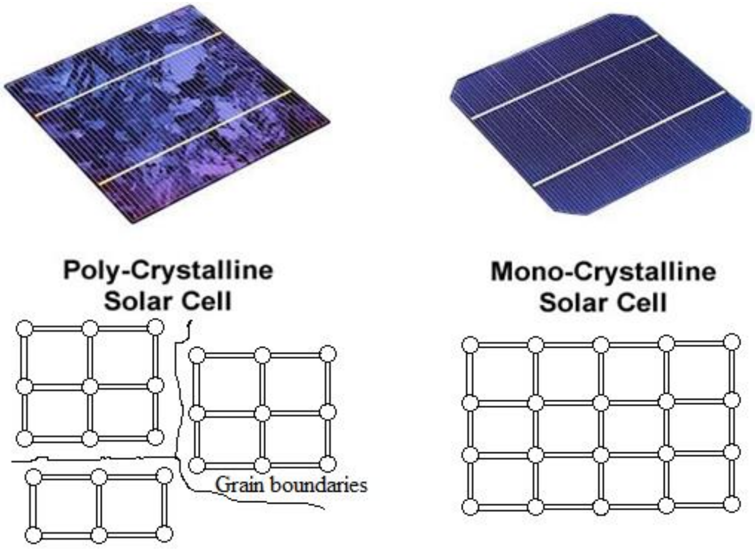

Figure 6. *Poly-crystalline and mono-crystalline silicon solar cells. Adapted from [10].*

Individual solar cells are rarely used on their own. Instead, a number of solar cells with similar characteristics are connected to each other to form a solar module. The cells are connected in series so that the desired voltage is achieved. In addition to the actual solar cells, a solar module includes other devices such as the wiring and bypass diodes. Bypass diodes are important components of a solar module. They are used to diminish the power losses caused by shading and soiling. Trees, buildings or other solar modules could shade the module. Without bypass diodes, if one cell is shaded, the whole module's power would be decreased. Bypass diodes also prevent overheating and damage caused by shading and soiling. A solar module and a residential PV system consisting of 12 solar modules is presented in Figure 7.

Figure 7. *Naps solar module and residential PV system [11].*

The figure shows a residential 2.4 kW PV system on a detached house located in Åland, Finland. Typically, a residential small-scale domestic solar system can be installed on a roof in less than one day. [11]

2.2.1 Operating principle of a solar cell

Silicon-based solar cells consist of two semiconductors that form a pn-junction. The n-type semiconductor is formed by doping the crystal structure of the silicon with phosphorus (or any other element from Group V of the periodic table). All the elements in Group V of the periodic table have five electrons in their outer energy shell, while silicon has only four. Therefore, each added phosphorus atom, produces one free electron. The p-type semiconductor is formed by doping the crystal with boron (or any other element from Group III of the periodic table). The elements from Group III of the periodic table have one electron less than silicon in their outer shell. Therefore, the bond boron forms with the surrounding silicon atom creates an electron vacancy, or “hole”. This hole can be regarded as a positive charge carrier. The basic idea of doping the silicon is thus to have excess electrons on the n-side of the cell, and excess holes on the p-side.

As the p- and n-type semiconductors are combined, a pn-junction is formed. Near the junction of the two semiconductors, the excess electrons on the n-side fill the holes on the p-side because of the diffusion effect. An area where there are very few or no free charge carriers is called a depletion region. Positively charged ions are formed on the n-side of the depletion region (where electrons were initially present) and negatively charged ions are formed on the p-side of the depletion region (where the holes were initially present). This, in turn, creates a positively charged area on the n-side and a negatively charged area on the p-side. There is thus a difference in electric potential across the area, so an electric field is formed. The direction of the flow in the electric field is from the n-side to the p-side. A pn-junction and its depletion region is illustrated in Figure 8.

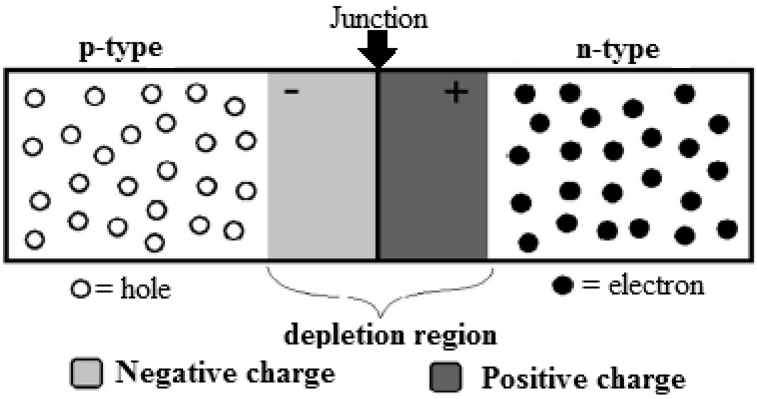

Figure 8. *Pn-junction and depletion region. Adapted from [7].*

The depletion region, as its name implies, depletes the number of mobile charge carriers. As a result, the depletion region is highly resistive and now behaves as if it were pure crystalline silicon. In other words, it acts as an electrical insulator. The resistance of the depletion region can be modified by connecting it to an external electric field. If the connected electric field is in the same direction as the electric field in the pn-junction, the depletion region's resistance will become greater, and vice versa. Therefore, the depletion region can be used as a voltage-controlled resistor.

If a positive voltage is connected to the p-side, and a negative voltage to the n-side, then the junction is forward-biased. This means that the external field and the existing electric fields are flowing in opposite directions. Therefore, the resulting field lowers the resistance of the depletion region. If the connected voltage is high enough (in silicon, around 0.6 volts) the resistance of the depletion region becomes negligible, and current can flow uninterrupted.

The solar cell works because of the photovoltaic effect. This is best described by considering the sun as transmitting radiation in certain packages, or quanta. In electromagnetic radiation these quanta are called photons. As a photon collides with an atom of the crystal structure in a solar cell, its energy is used to ionize an electron from the atom's valence band to the conduction band. This ionization only occurs if the photon has enough energy to ionize the electron over the band gap. During ionization, the electrons that are normally involved in a silicon bond are excited by the photon, which causes the bond to break. Photon collision is illustrated in Figure 9.

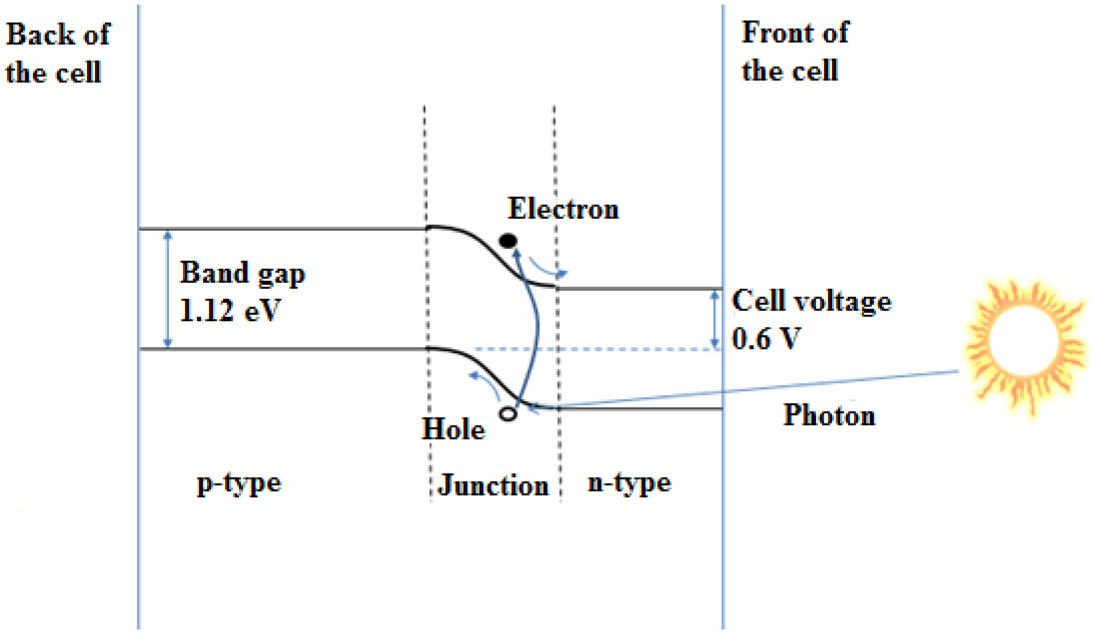

Figure 9. *Photon collision. Adapted from [12].*

The photovoltaic effect actually occurs even if the silicon is not doped, but because of massive effect of recombination, an undoped silicon cell couldn't produce enough power to be useful. In a pn-junction, however, a free electron-hole pair is produced, and because of the electric field in the depletion region, the electron and the hole separate and move to opposite sides of the junction, as shown in Figure 9. As long as the solar cell is part of an electric circuit, the charge carriers will form an electric current. Solar cells generate direct current, so grid-connected systems need an inverter to convert the direct current into alternating current.

2.2.2 Voltage-current -curve

The power of the photovoltaic solar cell, P (W), can be calculated with

$$P = VI \qquad (2.2)$$

where V is the voltage in Volts and I is the current in Amperes.

A solar module's nominal power is usually expressed as W_p (Watt-peak). A solar module's nominal power is measured in a laboratory under standard test conditions (STC). In standard test conditions, solar irradiance is 1000 W/m^2, the cell's operating temperature is +25 ^{0} C and the solar spectrum is at an air mass of 1.5 (AM1.5), which means the spectrum is the same as if the sun's zenith angle was $\theta = 48{,}2^0$. [3]

The open-circuit voltage, V_{oc}, is a cell's maximum voltage. Open-circuit voltage is achieved when the cell is not connected to a load and the current is 0 A. The short-circuit current, I_{sc}, is a cell's maximum current. The short-circuit current is achieved when both of the cell's electrodes are connected to each other and the voltage is 0 V.

When either the current or the voltage are 0, the power is also 0 W. Hence, power cannot be produced in open-circuit or short-circuit conditions. The highest power is achieved when the cell is functioning at its maximum power point (MPP). A cell does not automatically operate at MPP, so most solar inverters are equipped with maximum power point tracking (MPPT). A solar cell's voltage-current -curve, power curve and maximum power point, P_{max}, are illustrated in Figure 10. In the figure, I_m represents the current and V_m represents the voltage at the maximum power point.

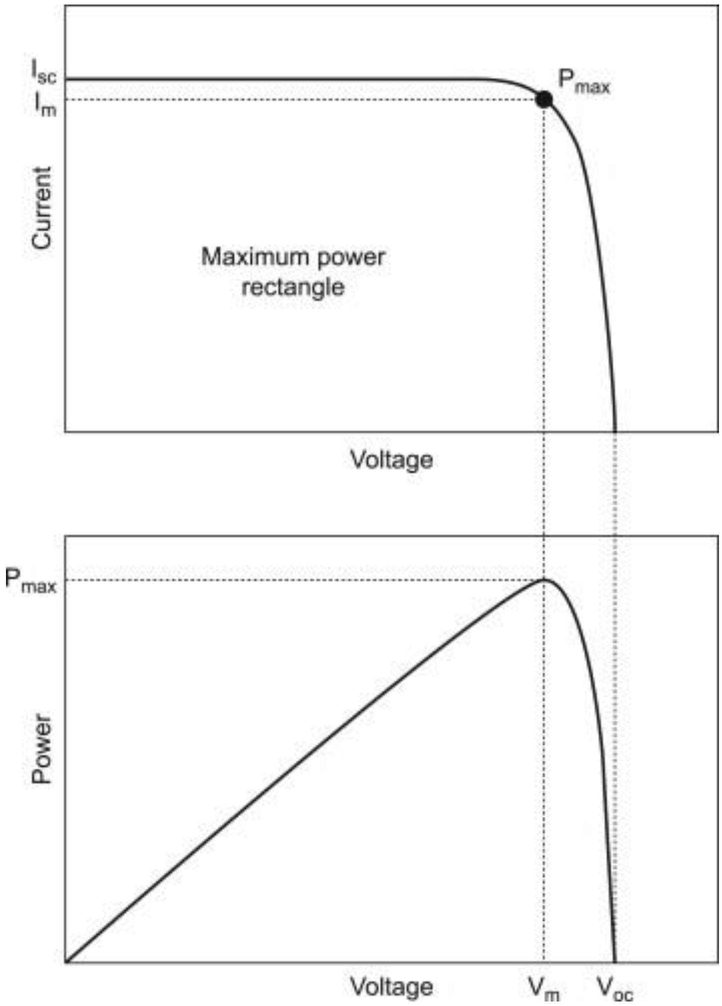

Figure 10. *Example of solar cell's voltage-current -curve and maximum power point [13].*

The energy, E (J), generated by the solar cell is derived from

$$E = \int P(t)\,dt. \tag{2.3}$$

Kilowatt-hours (kWh) are the most commonly used unit of energy in electrical engineering and the solar power industry. 1 kWh is 3.6 MJ.

The efficiency, η, of a solar cell is derived from

$$\eta = \frac{P}{GA} \tag{2.4}$$

where G is the intensity of the solar irradiation (W/m^2) and A is the solar cell's surface area (m^2). For example, the Naps Saana 255 TP3 MBW-solar module has an efficiency of around 16 % in standard test conditions (STC) [14]. However, the cell's efficiency under actual working conditions is usually less than this due to higher temperature.

A solar module system's utilization period of the maximum load can be calculated as

$$t_h = \frac{E_a}{P_{nom}} \tag{2.5}$$

where E_a is the annual generation of electricity and P_{nom} is the nominal power of the module or system. Table 1, below, shows some publicly available system information as examples of the utilization period of maximum load. These systems have been randomly chosen from existing systems in Finland with above 20 kW power [15]

Table 1. *Publicly available system information. Adapted from [15].*

System	Power (kW)	Energy (kWh/a)	t_h (h/a)
Kampusareena, TUT, Tampere	59.1	46 005.8	779.1
Pori Swimming Complex	52.5	42 153.8	802.9
Karikontie, Mikkeli	49.5	41 044.4	829.2
S-Market Tuira, Oulu	46.3	28 178.9	608.6

As can be seen from the table, a typical utilization period of maximum load is around 800 h/a. The system in Oulu has a somewhat lower than normal value, but this can be explained by the effects of shadowing and the lower irradiance in more northerly latitudes.

2.2.3 Operating conditions affecting PV generation

Operating conditions have a significant impact on the operation of a solar cell. The cell's current is almost linearly connected to the amount of solar irradiation. This is because the more photons that hit the surface of the solar cell, the more free charge carriers will be created. The intensity of the solar irradiation also affects the voltage, V, but this isn't so significant. The effects of variable solar irradiance are illustrated in Figure 11.

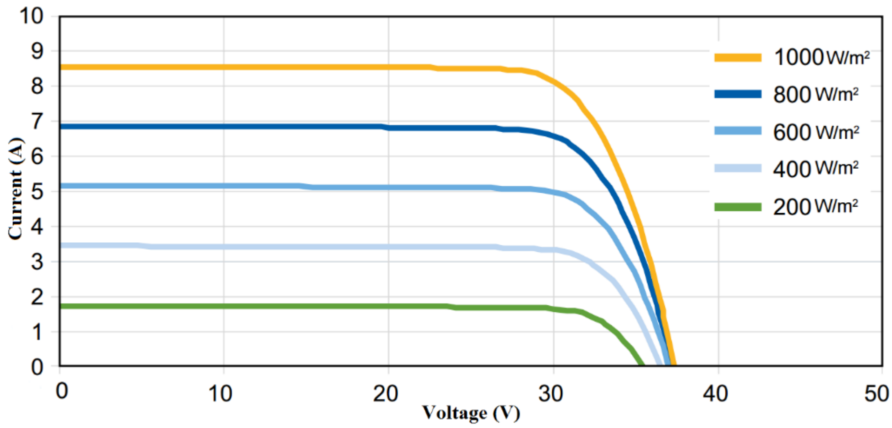

Figure 11. *I-V characteristics of Naps Saana 245 TP3 MBW at constant temperature of 25 ^{0}C and variable irradiance level. Adapted from [14].*

Temperature also has an effect on PV generation. As the temperature rises, the inner electric field of a pn-junction decreases because the energy of the silicon's electrons increases. Therefore, photons with less energy are able to ionize electrons, so the current in the cell increases. However, this increase in current is insignificant compared to the decrease in voltage. Higher temperatures increase the concentration of free charge carriers. As this happens, more electrons in the valence band are excited into the conduction band because of the increase in thermal energy. Therefore, more electrons and holes are separated on each side of the inner electric field. This affects the equilibrium of the depletion region by decreasing the inner electric field. This, in turn, decreases the open-circuit voltage. Figure 12 illustrates solar modules' I-V characteristics at various temperatures.

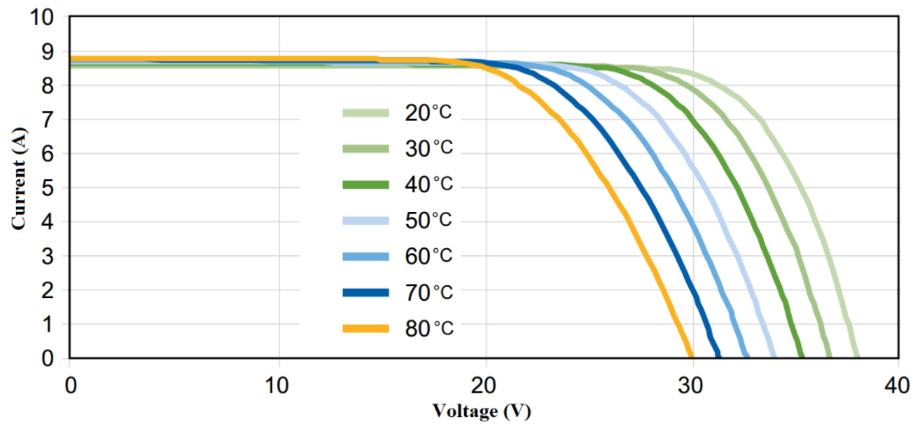

Figure 12. *I-V characteristics of Naps Saana 245 TP3 MBW at various temperature with a constant irradiance of 1 kW/m^2. Adapted from [14].*

As the figure shows, the temperature has a significant impact on a solar module's voltage. As the operating temperature increases, the power, P, decreases and vice versa.

2.2.4 Orientation and inclination

The power generated by a solar module is at its peak when the solar irradiance is most perpendicular to the module's surface. Therefore, some photovoltaic systems are equipped with a solar tracking system so that each module is always directly facing the sun. However, this method is not cost-effective, so most solar modules are installed in a stationary position. Therefore, solar modules are not always working optimally. The optimal inclination in Finland for every month of the year is illustrated in Table 2.

Table 2. *Optimal inclination for every month in Tampere [16]*

Month	α_{opt}	Month	α_{opt}
January	78^0	July	25^0
February	73^0	August	35^0
March	59^0	September	51^0
April	44^0	October	63^0
May	30^0	November	73^0
June	22^0	December	80^0

In Finland, (high northern latitudes) the optimal inclination varies greatly depending on the season. In Tampere, the optimal inclination is $\alpha_{opt} = 42^0$ [16]. However, because of techno-economic factors, solar modules are rarely inclined optimally for energy production. Indeed, the cost of the modules has decreased so much that it is cheaper to simply install a few more modules into the system, rather than installing each module at its optimal angle.

Orientation is another factor affecting the energy production of solar modules. The optimal orientation in the northern hemisphere is $\theta_{opt} = 0^0$, which means that the solar modules are facing directly south. Modules facing east have an orientation of -90^0 and modules facing west have an orientation of $+90^0$. The effects of orientation on the energy production of solar modules are illustrated in Table 3.

Table 3. *Effects of the modules' orientation on energy production [16]*

Orientation (θ)	0°	±10°	±20°	±30°	±40°	±50°	±60°	±70°	±80°	±90°
E_{annual} (%)	100	99,6	98,8	97,4	95,1	92,5	89,3	85,7	81,6	77,1

The table shows that even at an orientation of ±50°, the energy production is over 90 % and at an orientation of ±20° the energy production is almost 99 %. It can sometimes be beneficial to install solar modules facing east and west for residential use without a BES system, so that the power generation follows the load more closely.

2.2.5 The Balance of System

As well as the PV modules, a photovoltaic system includes a number of other different components. These components constitute the balance of the system (BOS). BOS includes, for example, the wiring, a mounting system, inverters and switches. It would also include the battery energy storage system (BES) and the associated charge controllers.

Other possible components are a maximum power point tracker (MPPT), energy management software, solar concentrators, solar irradiance sensors and other weather sensors. In addition, the land or building where the PV system is situated may sometimes be included in the BOS.

The components that are needed in a grid-connected PV system are illustrated in Figure 13. In addition to these components, a PV-BES system also needs battery energy storage and additional power electronics.

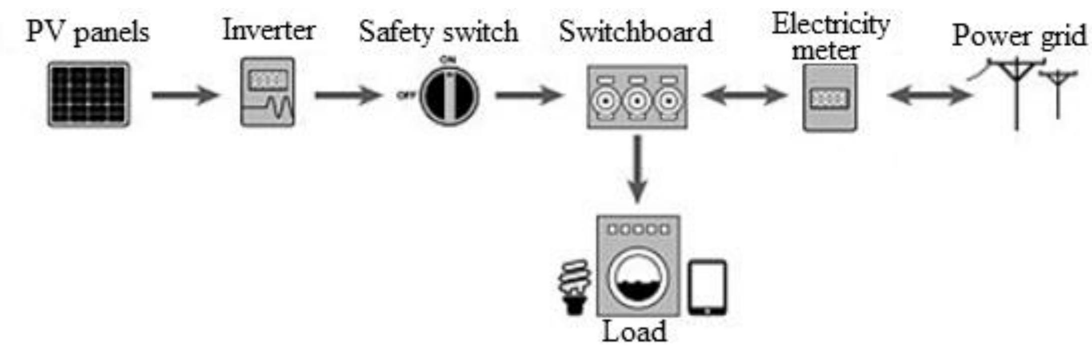

Figure 13. *Components of grid-connected PV system. [7]*

All of the components have to be wired together, so the wiring is a mandatory component of any PV system. Nowadays most of the safety equipment is integrated into the inverter, and the mains distribution board and electricity meter are usually already installed in the residence.

The inverter converts the direct current from the photovoltaic generation to alternating current, compatible with the national grid. Under 3 kW_p PV systems are usually connected with a 1-phase inverter. As the nominal power of the PV system increases, 3-phase inverters must be installed. With a 3-phase inverter, the solar power can be used in all of the loads in the residence. With a 1-phase inverter, the solar power can only be used for devices in that phase, which means that the demand from the other two phases must be drawn from the grid. [6]

2.3 Photovoltaics; globally and in Case Finland

Globally, the cumulative capacity of photovoltaics has increased greatly in recent years. Europe had long been at the forefront of the photovoltaics industry, but nowadays China and the USA, for example, have made significant investments in the field, as is illustrated in Figure 14.

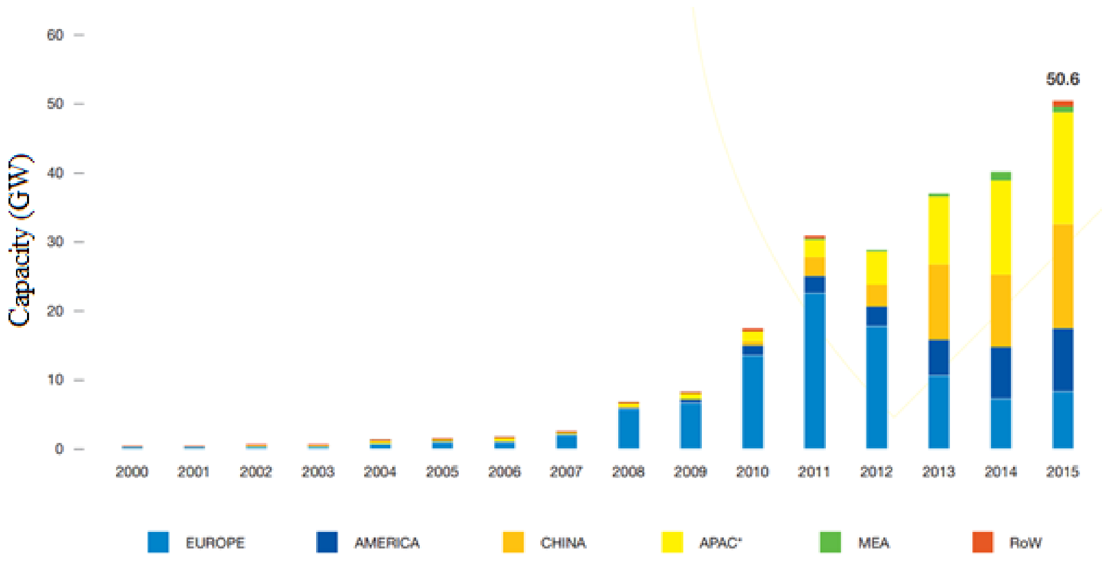

Figure 14. *Installed capacity of PV per year. APAC = Asia Pacific excluding China, MEA = Middle East and Asia, RoW = Rest of the World [17].*

Apart from a small drop in 2012, the annual installed capacity has increased steadily since 2000. In 2015, the globally installed capacity was 50.6 GW, which means that by the end of 2015, the total cumulative capacity was 229.3 GW, as can be seen from Figure 15.

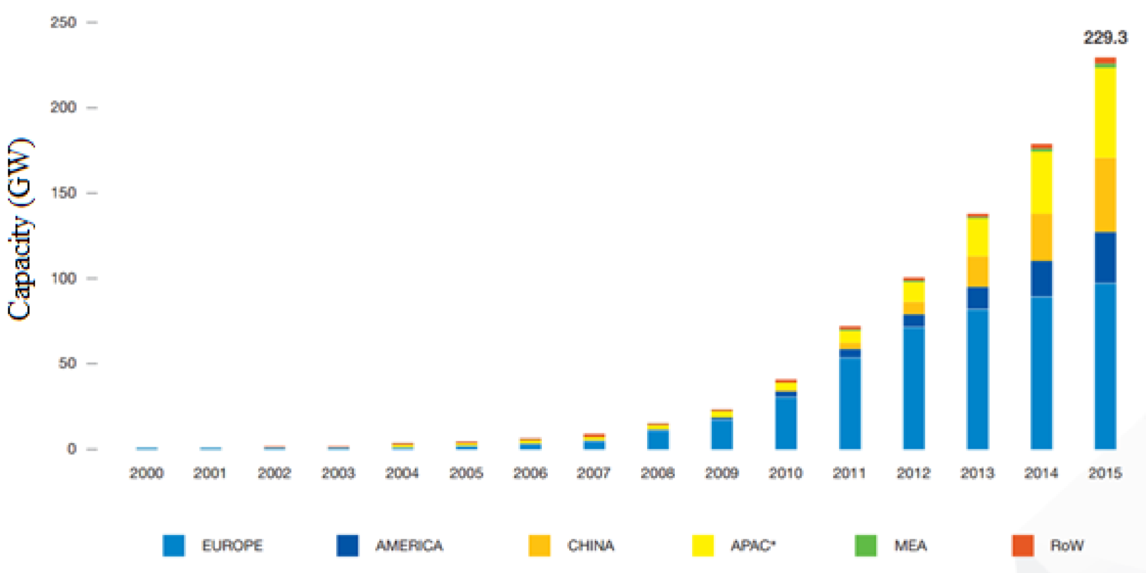

Figure 15. *Cumulative capacity of PV 2000-2014. APAC = Asia Pacific excluding China, MEA = Middle East and Asia, RoW = Rest of the World [17].*

Photovoltaics has clearly taken major steps towards becoming a significant energy source globally. A capacity of 229.3 GW means that approximately 229 TWh (with utilization period of maximum load of 1000 h/a) can be produced from photovoltaic energy.

Global electricity consumption being around 21 000 TWh/a [18], it means that 1.1 % of the world's total electricity consumption could have been provided by photovoltaics in 2015. If the spread of PV continues on its current trajectory (20%), then according to [17], global capacity could be anything from 500 GW to 700 GW by 2020 (see Fig. 16).

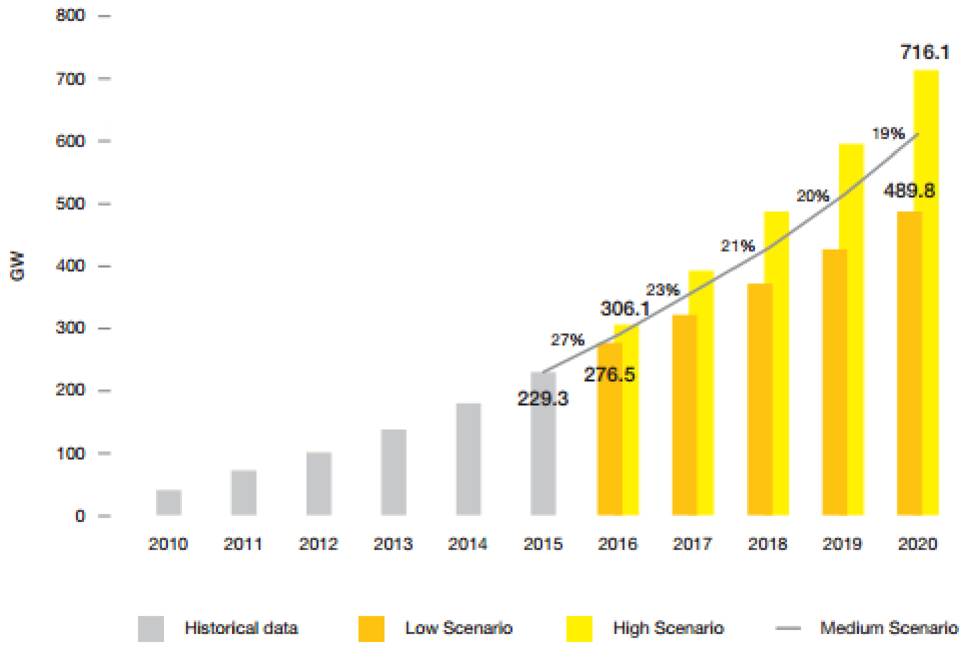

Figure 16. *Estimate of global PV capacity 2016-2020 [17].*

According to some estimates, global PV capacity could be around 716 GW within the next 3 years. If we compare this capacity and yearly energy yield (assuming t_h=1000 h/a) to the total global electricity consumption for 2015, approximately 3.5 % of electricity will be supplied from solar power.

It is not just globally that PV has increased. Despite its cold and harsh winters, the use of solar power has also increased in Finland in recent years. According to [19], the photovoltaic capacity increased in Finland from 7 MW in 2010 to 11 MW in 2014. These figures include both off-grid and grid-connected systems. Also, according to [20] there was 7.9 MW of grid-connected solar power in 2015. The latest figures indicate that by the end of 2016, the total grid-connected capacity in Finland was around 20 MW [20].

As can be seen in Figure 17, southern Finland has almost the same annual solar irradiation as much of central Europe (e.g. Germany). Therefore, the operating conditions and the possibilities of solar energy production are relatively good in this part of the country.

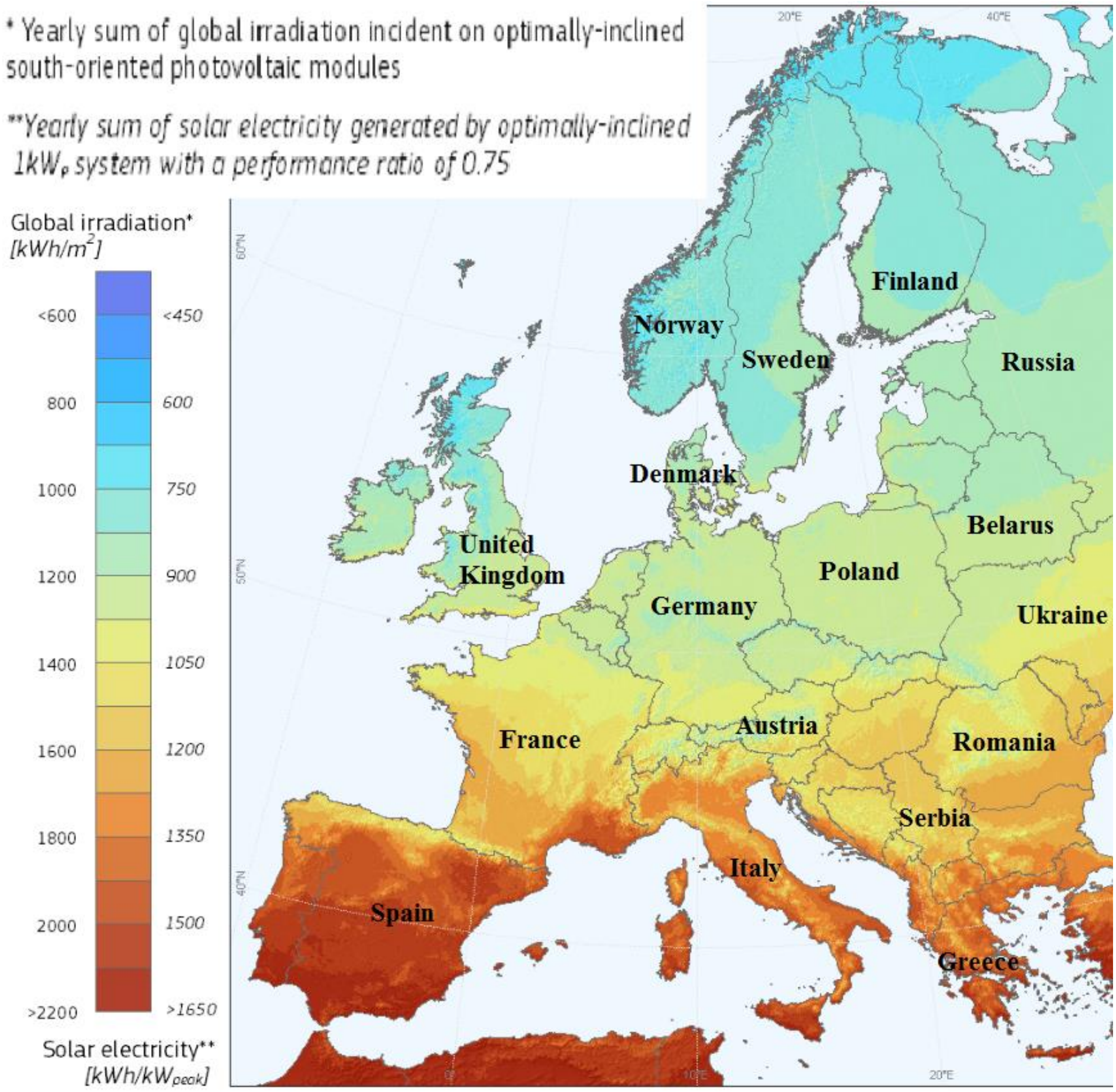

Figure 17. *Annual yield of solar power. Adapted from [16].*

The production capability in southern Finland is almost as good as in Germany, a country which has already installed much more solar power per capita than Finland has. The main problem in Finland is that the further north you go, the darker and longer are the winters. Obviously, in darkest wintertime, photovoltaic modules cannot generate electricity, and it is the same if the modules are covered in snow. So, any off-grid PV system in Finland needs a seasonal energy storage system, or its own diesel generator. However, in a grid-connected system, the climate is not such a big problem because the customer can draw power from the grid as and when needed. Another problem is that daily PV production and consumption rarely match each other very well, particularly for residential use. It would be most effective to use photovoltaic systems on sites where energy demand is stable around the year, or where the bulk of the energy demand occurs between spring and fall, such as in summer holiday resorts, or in Finnish summer cottages.

3. BATTERY TECHNOLOGY

Batteries appear to be the most promising form of energy storage for use in the Finnish residential sector. The basic concepts and components used in BES are introduced in section 3.1 and the most commonly used battery technologies are reviewed in section 3.2. Section 3.3 makes a techno-economic comparison of these battery technologies.

There are many other energy storage technologies in addition to conventional batteries. For example, there are flow batteries, hydrogen fuel cells, superconducting magnetic energy storage (SMES), super capacitors, flywheels, compressed air energy storage (CAES) or pumped hydro storage. Some of these technologies are discussed in section 3.4.

3.1 Basic concepts and components

A battery's operating principle is that it converts chemical energy into electric energy and vice versa. It does this by means of an electrochemical oxidation-reduction (redox) reaction. This type of reaction involves the transfer of electrons from one material to another through an electric circuit. [21]

While the term "battery" is often used, the basic electrochemical unit is more correctly known as a "cell." A battery consists of one or more cells, connected in series, in parallel, or both, depending on the desired output voltage and capacity. [21]

An electrochemical storage cell consists of an electrolyte (which contains dissolved ions) and two electrodes containing different active materials. The electrochemical reaction, which occurs when the cell is discharged, is as follows: the negative electrode gives up electrons to the external circuit and is oxidized during the electrochemical reaction. The positive electrode, accepts electrons from the external circuit and is reduced during the electrochemical reaction. When the cell is being charged, the electrochemical reaction is reversed and the electrons go in the other direction.

The electrolyte is between the two electrodes, and is the medium for the transfer of the ions between the electrodes. The electrolyte is typically a liquid, such as water, with dissolved salts, acids, or alkalis to impart ionic conductivity. Some batteries use solid electrolytes, which are ionic conductors at the operating temperature of the cell. [21]

The electrochemical operation of a cell is illustrated in Figure 18. The circuit on the left is discharging while the one on the right is charging. In the battery industry, the negative electrode is often called the anode and the positive electrode, the cathode. However, this is misleading because when the battery is charging, the anode and the cathode are reversed. This is because an anode is defined as the place where the oxidation occurs, or the electrode from which the electrons leave.

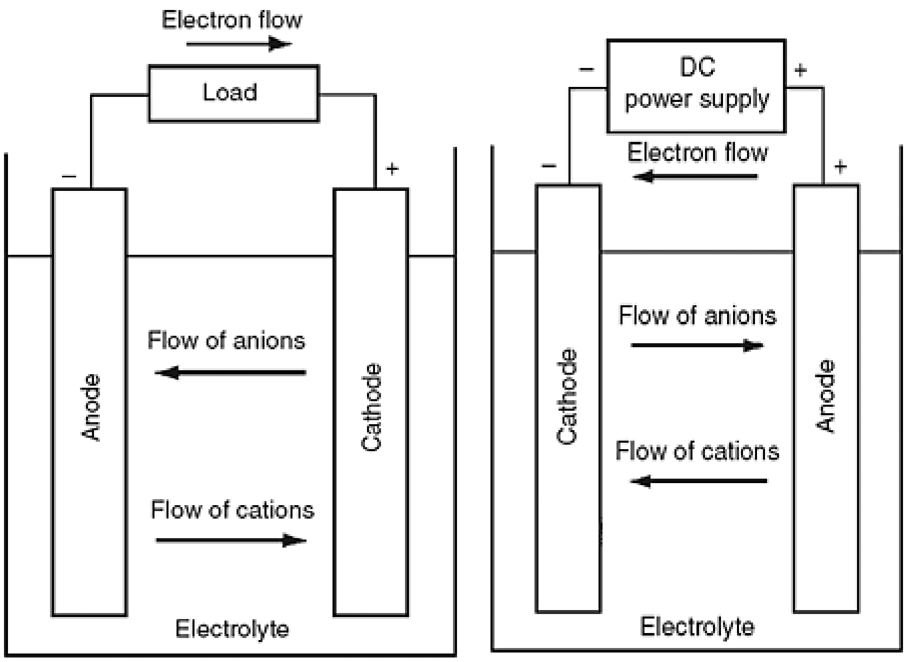

Figure 18. *Electrochemical operation of a cell. Discharging on the left and charging on the right [21].*

When the cell is connected to an external load, the electrons flow from the negative electrode, which is oxidized, through the external load to the positive electrode, where the electrons are accepted and the positive electrode is reduced. The electric circuit is completed in the electrolyte by the flow of anions and cations to the negative and positive electrodes, respectively. When a cell is being recharged, the current flow is reversed and oxidation takes place at the positive electrode and reduction at the negative electrode.

3.2 Currently available battery technologies

This section reviews the battery technologies possible for residential PV use. Each battery technology can be differentiated from the others by certain attributes such as capacity, power rating, cost, lifetime, cycling durability, efficiency, response rate, energy density and self-discharge. Cycling durability (also known as cycle lifetime) is a measure of how many full cycles (charged from zero to full and again discharged to zero) the batteries can last.

Battery energy storage used in residential PV system has to have certain characteristics. The capacity and power rating are dependent on power consumption and production. Because of the relatively high cost of installation and power electronics, it is best to use batteries which have a long lifetime and good cycling durability. The battery has to be efficient so that the energy used to charge it is not lost when the battery is discharging under a load. The battery's response rate has to be fast (seconds to minutes) because the load curve of a residential customer can be quite unpredictable. However, it does not need to have a superfast response rate in the order of milliseconds. The self-discharge rate for residential use shouldn't be much higher than 1 %/d.

Energy density is also an important factor although it is less important for domestic use than it is in an electric vehicle or in a mobile device. If the volumetric energy density is low, the battery energy storage would need a lot of space, which is at a premium in a small urban flat in Finland. The weight energy density is also important because the floor of the residence will need to be able to handle that weight. The temperature limits of the chosen battery technology also have to be considered, especially if the battery is to be installed in an unheated storage space in the winter. If the energy density is high enough, 2 kWh batteries used in a BES could be smaller than a microwave oven. Even a large residential BES system wouldn't need much more space than a small refrigerator, if batteries with a high energy density were used.

The following sections review the three most commonly used battery technologies: lead-acid batteries, lithium-ion batteries and nickel batteries.

3.2.1 Lead-acid batteries

Lead-acid batteries were the first rechargeable batteries and have been the most used battery technology ever since. It has often been forecast that they will be replaced with some other battery technology, but the lead-acid battery has kept its popularity. As well as many other plausible parameters, the lead-acid battery's main competitive advantage is its cost. [22]

As with the other battery technologies, the lead acid battery's operation is based on a chemical reaction. It uses lead dioxide as a positive electrode and lead as its negative electrode, and has sulfuric acid as an electrolyte. [22]

Lead batteries can be divided into two types, open and closed batteries. The first open battery was developed in 1859 by Gaston Plante. It was another 40 years before nickel batteries began to compete with them. Open lead batteries require maintenance, which means adding water to the battery from time to time. Open lead batteries have largely been replaced by closed batteries, mainly for safety reasons. Nevertheless, open lead batteries are still the more cost-effective type, with a higher energy density and a longer lifetime, so they can still be considered for applications where there isn't any risk from acid spray or spillage, or from hydrogen gas leakage. [22]

The first closed lead battery wasn't developed until the 1970s, 100 years after the invention of the first lead battery [23]. Closed lead batteries became very popular in the 1980s.

The main difference between open and closed lead batteries is that there isn’t any liquid electrolyte in closed batteries. Instead, the sulfuric acid is in the form of a gel or absorbed to glass mat (AGM). The discharge and charge reactions are the same as in the open battery, but as the oxygen and hydrogen do not leak out of closed batteries, there is no need to top up the water. For safety reasons, high-pressure release valves have been added to the batteries. [22]

One of the drawbacks with lead-acid batteries is that they have a very low energy density, so they are large. Another problem is that lead is highly poisonous for humans and animals, so they have to be disposed of in an environmentally-sensitive manner. Lead acid batteries are most suitable for applications where a robust, cost-effective battery is needed, whose weight and size are not a problem. They are generally used in cars, buses and boats as charging batteries, and some large industrial machines, wheel chairs, golf carts and other electric vehicles, and for emergency lighting and UPS-systems (uninterrupted power supply) in vital infrastructure services such as hospitals. They are also already used extensively in PV off-grid installations. [22; 23]

The advantages of lead acid batteries include their relatively low cost, the maturity of the technology and their relatively wide operating temperature range. The main disadvantages are their low energy density and their short lifetime [23; 24].

In short, lead acid batteries are cheap and reliable but heavy and bulky, so they could have problems in residential use.

3.2.2 Lithium batteries

The development of lithium batteries started in 1912, but advances were slow because of the instability of metallic lithium. Almost 60 years later, when the first lithium batteries began to appear on the market, they weren’t rechargeable. So the safety issues and the instability of metallic lithium meant that lithium batteries weren’t popular at first. A major breakthrough occurred when a lithium battery that used lithium ions instead of metallic lithium was developed. Sony commercialized the first lithium-ion batteries in 1991, since when lithium-ion batteries have become increasingly popular. [25; 26]

The main principle of the operation of the lithium-ion battery is the same as for the lead acid battery. There is an anode, a cathode and an electrolyte as a medium. When the lithium-ion battery’s electrodes are connected to a load, the positive lithium-ions in the anode travel through the electrolyte towards the cathode. At the same time, the electrons flow through the load from the anode to the cathode. When the battery is charging, the flow of electrons is reversed. [27]

Lithium ion batteries can be made from a wide variety of materials, but the anode is usually graphite. The material used in the cathode varies, so lithium ion batteries are usually named according to their cathode material, such as lithium iron phosphate, lithium cobalt oxide and lithium manganese oxide batteries. All the different combinations of anode and cathode materials have their own characteristics. For example, a lithium titanium battery has a longer lifetime and is slightly cheaper than the other lithium batteries, but it has lower energy density. On the other hand, a lithium cobalt oxide battery is more expensive and has a shorter lifetime, but it has very high energy density. [27; 28]

Lithium batteries have a relatively high energy density in general; around 150 Wh/kg compared to 25 Wh/kg for most lead acid batteries [29]. The disadvantages of lithium batteries are their cost and the danger of their overheating, when they can instantaneously combust with destructive force [25].

Because of their lightness, lithium ion batteries are most commonly used in mobile devices, phones, laptops, tablets etc., and also in small hand-held tools and devices. They are being used increasingly in electric vehicles, and also in small-scale energy storage systems [27; 28]. Current lithium-ion battery research is focused on decreasing the costs and on using them for yet larger applications. As can be seen from Figure 19, the price has dropped from 1000 dollars/kWh at the beginning of this decade to around 350 dollars/kWh now.

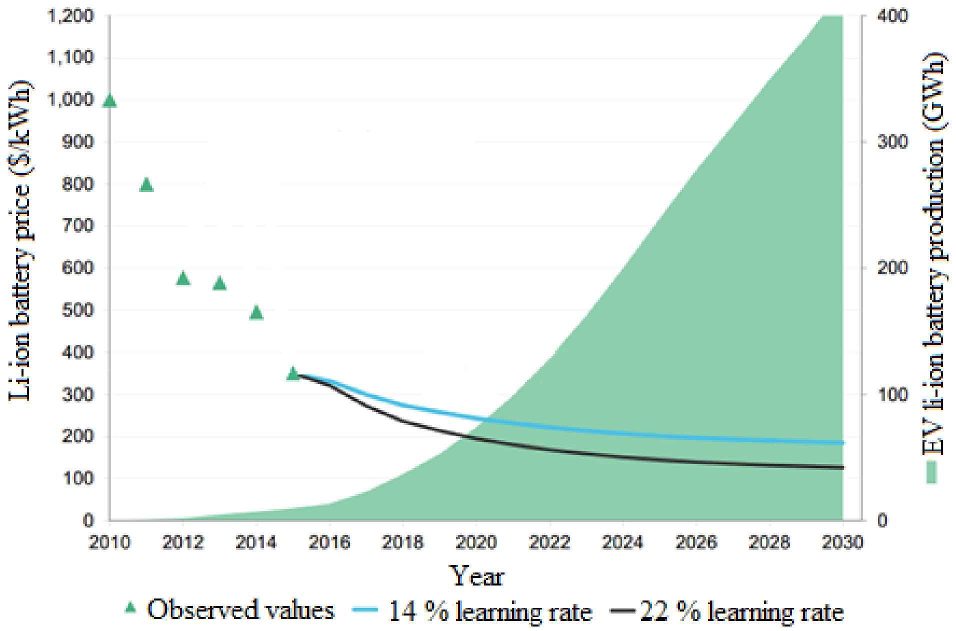

Figure 19. *Lithium-ion battery prices, historic and forecast. Adapted from [30].*

The learning rate or the price deduction is around 15 %. This has been driven by continual improvements in battery chemistry, processing and manufacturing the parts and materials, and greater economies of scale. Consumer lithium-ion batteries have exhibited a 22 % learning rate. Any further fall in the cost of lithium-ion batteries is more or less dependent on the development of such batteries for electric vehicles on a global scale. According to [30], with a 14-22 % learning curve, the price of lithium-ion batteries could be 130-180 dollars/kWh by around 2030. At today's exchange rate, (1,00 $ = 0,927 € [31]) this would be around 120-170 €/kWh.

According to one study [32], if the 13,000 kton global reserves of lithium (2012 estimate) were to be consumed at an annual rate of 34 kton, then our current reserves would last 382.4 years. However, with the potential expansion of the use of lithium batteries in portable electronics, electric vehicles and energy storage, then the lithium reserves would not last as long. However, even under the highest demand scenario for lithium battery technology, only half of the available resources would have been used by 2100. So, for the time being at least, the global reserves of lithium isn't a problem. [32] Indeed, if we include the possibility of recycling the lithium used in batteries, there should not be any pressing supply problem at all.

Lead-acid batteries, and other older types of rechargeable battery, can be easily configured by connecting individual cells in series and parallel and then using some external electronic controls to prevent over- and undercharge. However, larger lithium-ion batteries have to be built up from relatively smaller units with built-in electronic protection. Therefore, not only are there different battery chemistries to consider, but also different electronics packages, as even batteries with the same chemistry made by two different manufacturers might have quite different electronics. [33]

The main advantages of lithium ion batteries are their high energy density (both volumetric and weight), high energy-efficiency and long lifetime. On the other hand, they are expensive, and their tendency to explode when they overheat can be a problem. Nevertheless, lithium ion batteries have a wide range of different chemical compositions so their characteristics can vary greatly. [25]

3.2.3 Nickel batteries

The first nickel battery was developed in 1899 by Waldmar Jungner and it was immediately clear that it had many advantages over the lead acid battery. The development of nickel batteries was initially slow because of the limited availability of the material and its high cost. The first closed nickel batteries were made in 1947, after which they started to become more popular. [34]

From nickel batteries the best-known nickel batteries are the nickel cadmium, the nickel iron and the nickel metal hydride batteries. This last is the latest type, but the main principle of operation is the same for all of these different technologies. All the batteries have nickel-oxide hydroxide as the cathode and potassium hydroxide as the electrolyte. The anode, however, could be cadmium, iron or metal hydride.[34]

Nickel iron batteries were very popular at the beginning of the 1900s because of their long lifetime. For example, they were used in electric vehicles even back then. However, the nickel cadmium batteries were much less corrosive than the iron ones, and had a slower self-discharge-rate. For these reasons, nickel cadmium batteries had largely replaced nickel iron batteries by the end of the 1970s, so nickel iron batteries fell out of use. Nowadays, nickel cadmium batteries, or nickel metal hydrides are used rather than nickel iron, as they have much better performance. [34]

Currently, nickel metal hydride is the most commonly used nickel battery. This battery's development began in 1967, but because of instability issues it didn't really penetrate the market until the 1980s. During the 1980s and 1990s the sales of laptops and mobile phones boomed, which also accelerated the use of nickel metal hydride batteries. However, lithium ion batteries have developed remarkably over the last two decades, and they have largely replaced nickel metal hydride batteries for use in small-scale mobile devices. [34]

Nickel batteries have one major disadvantage over other batteries, which is the memory-effect. Particularly for nickel cadmium batteries, the capacity of the battery decreases if the batteries are not completely discharged and recharged. It is the same for all nickel batteries, but the effect is particularly noticeable in the cadmium ones. The problem can be avoided if the battery is completely discharged from time to time before it is fully recharged, besides which, as the battery technology has developed, the memory-effect has diminished.

Nowadays nickel batteries are mostly used in applications where neither lithium ion nor lead acid batteries can do the job, often in UPS-systems and hand tools. In terms of cost and energy density, nickel batteries fall somewhere between lithium and lead batteries.

As lithium ion batteries have replaced nickel metal hydride batteries in phones and laptops, the use of the latter two types has decreased dramatically. Nowadays nickel metal hydride batteries are most commonly used in hybrid cars, where their lower cost and safety characteristics make them more suitable than lithium ion batteries.

The main competitive advantage of nickel batteries is their wide temperature range. No other battery will work as well at extremely low temperatures (below -30 ^{0} C), if at all. Nickel-cadmium batteries also have the longest lifetime in extremely high temperatures.

Nickel batteries do not have any clear advantages for residential use compared to the other batteries, but nickel batteries can be competitive simply because of their overall averageness. The advantages of the nickel cadmium battery are its long lifetime, relatively low cost, durability (can be installed in harsh conditions), energy density (higher than lead acid battery but lower than lithium ion) and their operational reliability in variable temperatures. The advantages of nickel metal hydride batteries are that they have higher energy density than nickel cadmium batteries, and they are safer and more environmentally friendly.

The disadvantages of nickel batteries are the memory-effect, the toxicity of cadmium and a higher self-discharge rate than in lithium ion and lead acid batteries.

Overall, the main problem with the nickel cadmium battery is the toxicity of cadmium. None of the nickel battery's other characteristics give it any clear advantage over the lead acid or lithium battery, but it falls somewhere between the two. Therefore, it has a number of disadvantages in terms of energy storage but no advantages. [34].

3.3 Techno-economic comparison of batteries

Battery development has always been driven by contemporary demand. Currently, battery development is led by hybrid cars, electric cars and mobile devices, where high energy-density and weight energy density is needed. In residential battery energy storage, high energy density might not be the most important aspect. On the other hand, if the user only has a small space for the batteries, then the batteries' size could be a problem. Cost is obviously one of the main factors in battery energy storage. The cost has to be averaged out over the battery's lifetime in years, and in cycles, as the longer a battery's working life, the greater its cost-effectiveness.

Batteries haven't been developed specifically in terms of their use in residential applications, so all the different battery technologies may have applications for BESs. A comparison of the techno-economic factors of different types of batteries is shown in Table 4. In addition to lead acid, nickel batteries and lithium ion batteries, two types of sodium batteries are also included in the comparison. Sodium batteries are not yet widely used, but their relatively low cost could be their main competitive advantage. It should be noted that lithium-ion batteries include several different technologies, and they will be analyzed later in this chapter.

Table 4. *Techno-economic comparison of battery technologies [32]*

Battery	Cost (€/kWh)	Energy density (kWh/m^3)	Round-trip eff. (%)	Life-time (years)	Lifetime (cycles)	Operating temp. (°C)	Self-di-scharge %/day
Pb-acid	**50-300**	75	80–90	3–15	2000	-20 to +50	**0.1–0.3**
NiCd	200-1000	<200	70–75	**15–20**	1500	**–40 to +45**	0.2–0.6
NiMH	240-1200	<350	70–75	5–10	3000-5000	–20 to +45	0.4–1.2
Li-ion	200-1800	**250–620**	**90–98**	8–15	**>4000**	–10 to +50	**0.1–0.3**
NaS	200-900	<400	85–90	12–20	2000–4500	+300	20
NaNiCl	70-150	150–200	90	12–20	1000–2500	+270 to +350	15

Pb-acid and NiCd batteries are the most mature technologies, while all of the other technologies are fairly new. It seems unlikely that Pb-acid and NiCd batteries will be developed much further, but the cost of the other technologies might decrease over time. Further development of the newer types of batteries may make them still better for use in residential battery energy storage.

The memory effect of nickel batteries might be problematic in energy storage use because of the varied depth of load cycles and variable load currents. Nickel batteries also have very poor round-trip efficiency at around 70-75 %, and their costs are much higher than Pb-acid batteries, although they do cost less than lithium ion batteries. Nickel-cadmium batteries have a good lifetime in years, but in BES use it might not achieve that because of cycle lifetime. Nickel metal hydride batteries have a good lifetime in cycles, but not in years. For the above reasons, nickel batteries are excluded from the comparison.

Round-trip efficiency is one of the most important factors in battery energy storage use. The best round-trip efficiencies are in Li-ion, NaS and NaNiCl batteries. Sodium batteries have the longest lifetime in years, but for residential energy storage, the battery's lifetime in cycles might be the decisive factor. The high operating temperatures of sodium batteries also make their use in residential BESs very impractical. Their self-discharge rate per day is around 15-20 %, which negatively affects their overall efficiency.

The conventional lead acid battery has one big advantage: its cost. Lead acid battery technology is very mature so the cost of the batteries has decreased over decades of research and production. The price of the lead battery is largely determined by the market price of lead. The main drawbacks are its size and weight energy density, which are unlikely to be drastically improved in the foreseeable future. Lead batteries' round-trip efficiency, their lifetime in years and their cycle lifetime are all lower than in lithium-ion batteries. However, the lead-acid battery was included in the simulations because of its low capital cost.

Lithium-ion batteries are competitive in terms of overall lifetime in years and in their cycles. The high energy density of Li-ion-batteries is perhaps their biggest advantage over their competitors. They have very high round-trip efficiencies, which makes them relatively cost-effective. Currently, one of the main drawbacks with lithium-ion is its safety, as the press has recently been publishing stories about exploding lithium-ion batteries, which of course raises public concern. However, the cost of lithium-ion batteries is decreasing all the time because of their continued use in mobile devices, their increasing use in electric vehicles and also in energy storage solutions. On the assumption that [30] the lithium-ion battery learning curve is going to be around 14-22 %, the price of li-ion batteries should be 120-170 €/kWh by around 2030.

Many different materials can be used in lithium-ion batteries so every technology has its own characteristics. The main differences in the various lithium ion batteries is illustrated in Table 5. A minus sign means that the characteristic is lower in relation to the average lithium-ion battery, while a plus sign is higher than the average lithium-ion battery, with a double plus being much higher. A zero sign means it is average.

Table 5. *Comparison of lithium-ion battery technologies [6].*

Battery	Cost	Energy density	Lifetime	Cycle li-fetime	Safety
$LiCoO_2$	-	+	0	0	-
NCA	-	+	++	++	-
NMC	-	+	+	+	-
$LiMn_2O_4$	0	-	-	+	0
$LiFePo_4$	0	0	-	++	++

The main drawback with the lithium cobalt oxide ($LiCoO_2$), lithium nickel cobalt oxide (NCA) and the lithium nickel manganese cobalt oxide (NMC) batteries is their safety, which is an important factor in residential BES use. Their main advantage is their lower cost, and of the three types, the NCA is the best in other ways.

Lithium magnate oxide ($LiMn_20_4$) and lithium iron phosphate ($LiFePo_4$) are the cheapest and safest lithium batteries. However, the $LiMn_2O_4$ battery has lower energy density than average, and its lifetime in years can be shorter, as is also true of the $LiFePo_4$. However, the $LiFePo_4$'s safety and cycle lifetime (which improves its cost-effectiveness) are its biggest advantages over any of the other lithium battery technologies, which could make it the best choice for BES out of the lithium batteries. Overall, $LiFePo_4$ is a good compromise between many factors, and its cost-effectiveness and safety make it another battery technology to be studied with the simulations.

From the customer's point of view, the new technology of the lithium ion batteries is more appealing than that of the old lead acid batteries, so from an aesthetic viewpoint, customers might regard lead acid batteries as ugly and unappealing. This is one reason, a battery energy storage system with lithium ion batteries is recommended when choosing a new product for Naps Solar Systems. Of these, the lithium iron phosphate battery is the most promising.

3.4 Overview of other energy storage technologies

Every energy storage solution has its own application. Energy storages can be used, for example, in microgrids, commercial and industrial enterprises, or even on the mass utility scale. The intended use determines the desired discharge time and energy to power ratio, which are thus decisive factors. The three main types of use are:

- Short-term storage: seconds to minutes, energy to power ratio <1
- Mid-term storage: minutes to hours, energy to power ratio 1-10

- Long-term storage: hours to months, energy to power ratio >10

A comparison of the rated power, energy content and discharge time of different energy storage technologies is illustrated in Figure 20.

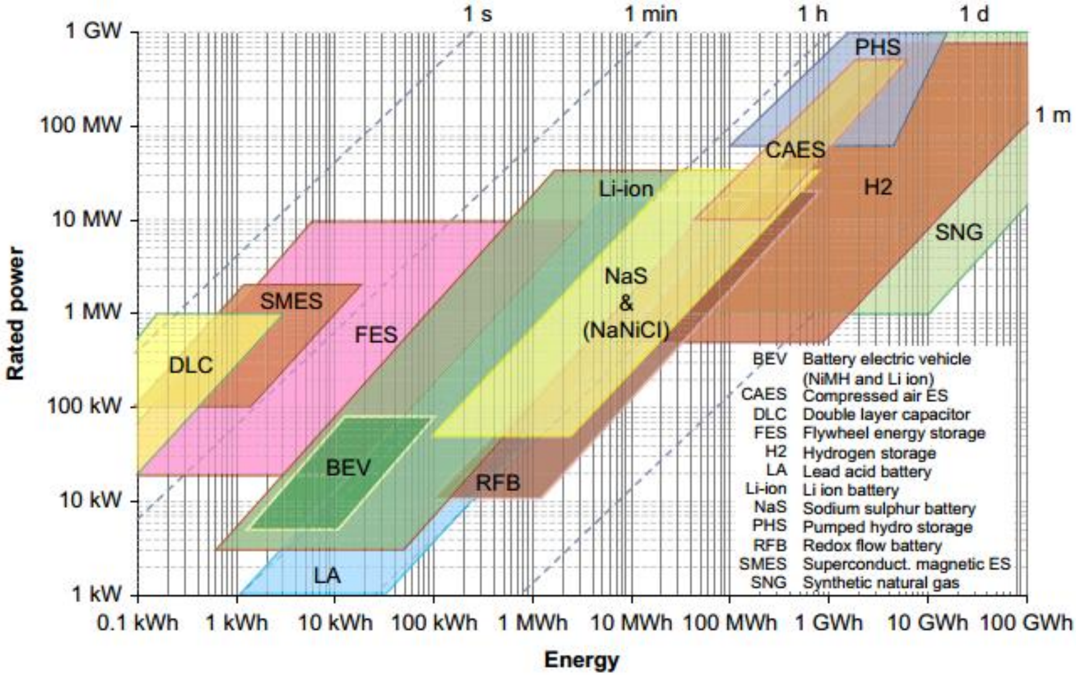

Figure 20. *Comparison of rated power, energy content and discharge time of different energy storage technologies. [35]*

For the MW/MWh scale, rechargeable batteries such as Li-ion, NaS and V-redox technologies are expected to be widely used, as they can all provide electricity for some hours or even days. For utility scale and long-term storage, compressed air storage (CAES), pumped hydro storage (PHS) and hydrogen fuel cells could be the solution. Short-term storage include superconducting magnetic energy storage (SMES) and flywheel energy storage (FES) for example. These could be used for rapid power balancing.

Energy storage technologies can be categorised as electromagnetic, electrochemical or mechanical systems. As well as the battery energy storage systems mentioned in sections 3.2 and 3.3, there are two other electrochemical energy storage technologies; flow-batteries and hydrogen fuel cells.

Flow batteries could be one possible future solution for residential energy storage. A flow battery is a cross between a conventional battery and a fuel cell. Although they don't look so good now, (the current investment cost is 1000-3500 €/kWh), flow batteries don't use any materials that would hinder the learning curve, so their future development should be watched.

Flow batteries differ from conventional batteries in that, whereas in conventional batteries the electrodes and the electrolyte are in the same space, in flow batteries there are two membranes, which are penetrable to the ions, but which separate the two electrodes. Two different electrolyte flow from separate containers to the power source and back to the tanks. The liquid electrolyte of metallic salts is pumped through a core that consists of a positive and negative electrode, separated by a membrane. The ion exchange that occurs between the cathode and the anode generates electricity. This is shown in Figure 11. [36]

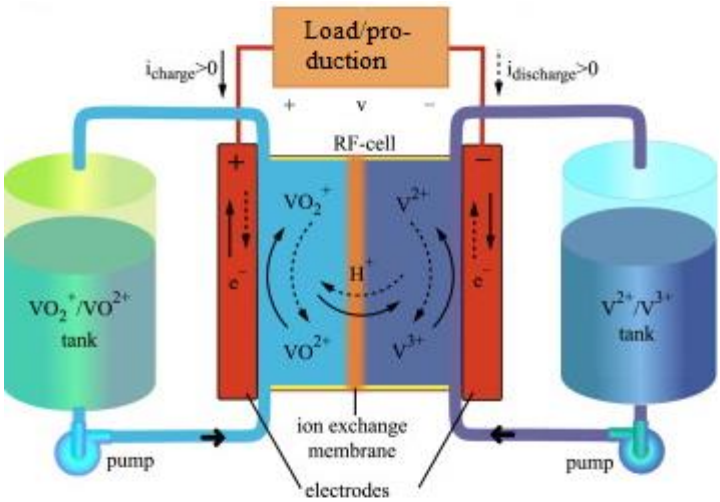

Figure 21. *Flow battery. Adapted from [36].*

Activated by pumps, flow batteries perform best on a scale above 20 kWh. They are said to deliver more than 10,000 full cycles, and are good for about 20 years. Each cell produces 1.15–1.55 volts, and they are connected in series to achieve the desired voltage levels. The battery has a weight energy density of about 40Wh/kg, which is comparable to a lead acid battery. As with fuel cells, their power density and ramp-up speed are moderate, which makes them best suited for bulk energy storage, but less so for electric powertrains and load leveling, which require quick action. [36]

Their construction might make them particularly good for residential use, because the power source and the electrolyte tanks can be completely separate from each other. In addition, their power and energy capacity can be sized independently of each other, as needed. In practice, the flow battery's capacity only depends on the size of the electrolyte tanks. At the moment, Vanadium-redox and zinc-bromide applications seem to have the most potential for the future development of flow batteries. Their characteristics compare pretty well with almost any other battery, and especially the vanadium-redox flow-battery has a very quick charging time. This means that they can be charged with a high current without compromising their efficiency. However, further research is still needed if flow batteries are to ever become commercially viable, as at the moment they are costly, and not very efficient [36]

Hydrogen fuel cells have the best potential for longer-term energy storage (days to months). They could be appropriate for seasonal storage here in Finland, but they need much further development. Fuel cells working with hydrogen do not have high storage efficiencies, so they are not yet commercially available in large volumes.

Electromagnetic energy storage systems include, for example, superconducting magnetic energy storage (SMES) and super capacitors. They are both high power storage devices and could be used for energy storage on the utility scale, offering quick power balancing and so on, but they are unlikely to be of use in residential-scale energy storage solutions. SMESs could possibly be developed so that they could be used on a residential scale, but the technology is not there yet. The biggest issue with SMES is that they need very expensive materials, and a cryogenic system that can keep the temperature close to absolute zero.

Mechanical energy storage systems include flywheels, compressed air energy storages (CAES) and pumped hydro storage (PHS). The flywheel's high self-discharge rate (20-100%/d) [32] makes it impractical for this kind of energy storage solution. Compressed air energy storages and pumped hydro storages are as yet impractical in residential or commercial energy storage use, but they may well be developed, as even today they are widely used on the utility scale.

4. BATTERY ENERGY STORAGE SYSTEM

A domestic battery energy storage system will store any surplus energy generated by the customer's PV system when the customer doesn't need it. This stored energy can be used in the evenings or during the night. An intelligent storage system can adjust the energy use so that most of the self-generated solar energy is at the customer's own disposal. This kind of intelligent system is often also able to draw power from the grid, so it can take advantage of the lower prices for grid electricity when demand is low, and use the stored electricity when the demand, and therefore the price, is high. In addition to batteries, home battery energy storage systems often include an inverter and other power electronics, an intelligent energy manager, measurement technology and the software to operate the system. These systems could also offer home energy management and also the possibility of monitoring and even controlling the system through an internet link from one's computer or smart phone.

Unless the issue is dealt with now, the increasing use of intermittent renewable energy sources, such as solar and wind, will cause problems for any grid, through, for example, overproduction and varied frequency. Besides grid extension and the development of demand-side management solutions, the ability to store electricity is becoming ever more important in the search for a carbon-free energy system. Although this isn't a problem yet for the Finnish grid, from the customer's point of view, it could become one. PV production is intermittent and usually poorly matched to the load curve of the residential user. With BES systems, excess PV production can be consumed during times of high demand hours, as shown in Figure 22.

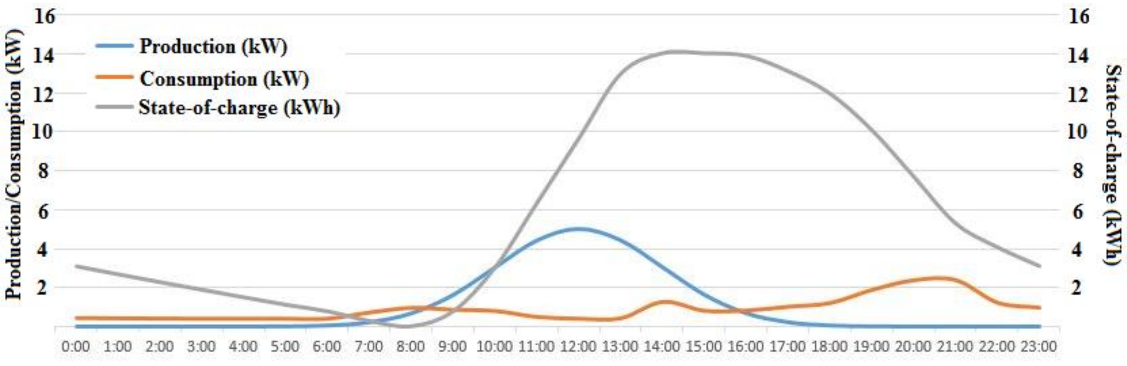

Figure 22. *PV production (5 kW PV system), load curve of residential customer (without electric heating) and the state-of-charge of the battery (14 kWh BES system).*

Usually PV generation is highest at midday, whereas the demand from the residential user is highest in the mornings and evenings. It is clear that peak production and peak demand are rarely matched, so without battery energy storage, surplus energy has to be sold to the grid operator at a low price.

A grid-connected PV-BES system battery could also be used for ‘peak-shaving’ and ‘time-of-use’ shifting. Shifting the time-of-use means shifting the energy taken from the grid from periods of high demand (and prices) to periods of low demand. The energy the domestic consumer draws from his BES, and the energy he draws from the grid can be adjusted to the benefit of the customer. It goes without saying that in off-grid systems, a battery storage system is a necessity, because no energy could be used at night time without it. Ten of thousands of off-grid systems with BES have been installed in Finland over the recent decades, but an on-grid system with storage BES is a fairly new application

Traditionally, PV systems have always been designed to minimize overproduction, because of the low selling price for the excess electricity. With a grid-connected BES, however, it might be more beneficial to oversize the PV system because there would be more opportunity for self-consumption.

4.1 Smart control and topologies

In off-grid systems, the BES is usually attached directly to the photovoltaic system through a device called a charge controller. The charge controller (CC) handles the charging and discharging of the battery, so that overcharging or over discharge cannot occur. The BES is then attached directly to a DC-load and/or to a DC-AC-inverter for AC-loads. If the system were attached directly to a DC-load, this would require demand-side management in order to avoid over-discharge. There is usually low voltage disconnect functionality in the inverter which handles this situation. This system is illustrated in Figure 23.

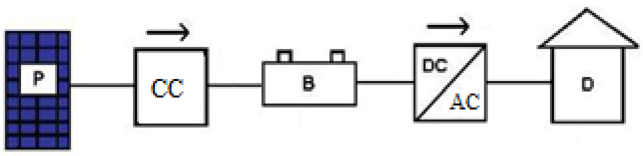

Figure 23. *Conventional off-grid PV system with battery.*

A BES system used in a grid-connected PV system often includes a smart controller. This takes into account the state-of-charge (SOC) of the battery to prevent overcharging and over discharging. However, it also has many other functions. Smart control can optimize the usage of the BES depending on the load, weather forecasts and even electricity price data. It can store any surplus energy from the PV system, and also charge itself from the grid when the electricity price is at its lowest point. It can also predict future electricity demand and could charge the battery so that it is ready for the predicted higher demand. For example, if the weather forecast says it’s going to be cloudy the next day, the BES can be charged from the grid while prices are low, rather than having to purchase power from the grid when the price is high. Although not all BES systems can do all of these things, they are all feasible options for integration into any modern grid-connected BES.

The conversion of the direct current from the battery into the alternating current used in domestic electrical appliances, and the grid, is done with an inverter. Most Smart Control units are integrated in the inverter, but they can also be separate units. Two possible topologies for PV-BES systems with the control units integrated into the inverters are illustrated in Figure 24. [37]

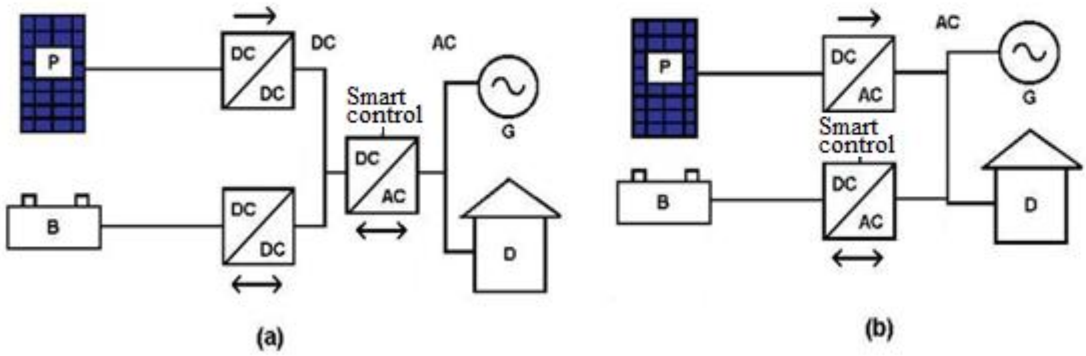

Figure 24. *PV-BES topologies. Adapted from [38].*

If the generator is already connected to the grid with a DC/AC-inverter, the BES can be connected to the grid with a bidirectional DC/AC- inverter, which includes the smart control unit, as illustrated in Figure 24 (b). The alternative is to connect both the PV and BES systems through one bidirectional DC/AC-inverter, as shown in Figure 24 (a), but this topology also needs two DC/DC-converters for voltage modulation. The Smart control is integrated in the bidirectional DC/AC-inverter as in topology (b). There are products on the market where the same kind of topologies are integrated into one system. [37]

A PV system consisting of the PV modules and a DC/AC-inverter is not affected by the integration of a battery in topology 24 (b). It is relatively easy to install a BES into existing PV systems. Topology 24 (b) is also modular and the sizing of both systems are independent of each other. The main disadvantage of this topology is its cost, as it needs two full inverters.

It can be more cost-effective to use Topology 24 (a) in new PV-BES systems, because only one DC/AC-inverter and one or two DC/DC-converters are needed, and such systems are therefore more efficient. However, both systems need to be sized accordingly, and if the BES system is installed into an existing PV system, the power electronics usually need to be changed.

All in all, topology 24 (b) seems to be the most promising one because this kind of BES system could be installed in parallel with an existing PV system. Therefore, this is the topology recommended for Naps Solar Systems Oy.

4.2 Benefits of Battery Energy Storage System

This study is mainly concerned with the monetary benefits of a BES system from the customer's point of view. However, BES systems also have many other benefits that cannot be quantified in monetary terms, so these will also be included in this review. From the customer's point of view, a BES system makes the customer energy-independent, so the customer can rely more on his own solar power than on other sources of energy. If the BES system has UPS-functionality, it can guarantee uninterrupted power supply, even during power cuts.

The monetary benefits arise mainly from the storage of excess PV production for later use. The cost of the electricity can then be compared to what it would have been without a BES system. In this case, all PV excess production has to be valued at its selling price, i.e. the price you can get if you sell it to the grid. The selling price for the customer only includes the price of the electricity, unlike the selling price from the grid, which includes not only the cost of the electricity, but also the charges for energy transfer, and taxes. Thus, for the customer, the electricity he can store in his BES costs considerably less than the electrical energy he can purchase from the grid, not just because the electricity company has to take its own cut from the profits. Another monetary benefit of BES comes from time-of-use (TOU)-shifting. In TOU-shifting, the battery is charged when electricity prices are low and discharged when electricity prices are high. There is a profit for the owner of a PV-BES system, too. Of course, in both of these metrics, the usual system losses have to be taken into account, and these, plus the round-trip efficiency, are factors that must be taken into account.

Two other possible monetary benefits could come from peak shaving and from the savings gained through having an uninterruptible power supply (UPS). In the residential sector, the cost benefits of an uninterruptible power supply are hard to quantify. For example, customers in rural areas where the grid supply is quite often interrupted might not be so interested in the savings per se, but in the fact that a BES system is capable of giving them a UPS. However, electricity distribution companies in Finland have already started to shift from overhead to underground cables in even quite remote rural areas in order to mitigate weather-related malfunctions, and underground cables have long been extensively used in cities and urban areas.

Although the UPS capability of a PV-BES is a clear benefit to certain customers, the savings from peak shaving and diminished power demand can be simulated and calculated more accurately. If customers could change to a smaller fuse size, for instance, then the transfer price would be lower. It is also possible that, in the future, distribution companies might change their pricing policy, basing it more on power than energy, in which case a BES system could contribute even more savings.

Energy storage in the residential sector also benefits the grid operators and energy companies. With widespread domestic energy storage, electricity peak demands could be shaved, and thus the whole electricity demand from residential customers with PV-BES systems would be more stable. The residential customer uses electricity mainly when the demand from industrial and commercial consumers is low, which would mean that reserve power generation would not be needed as much as it is now. Indeed, residential BES could be regarded as power reserves for the grid operators themselves, which would facilitate the management of the national grid. This would also be profitable for the customer.

It is, however, clear that if energy storages were to be be utilized on a wider scale in the future, the demand for electricity could become more stable. Ironically, this would lead to more stable electricity prices, so the profitability of energy storage could be lower. From the grid operator's point of view this should mean that the transfer capacity of the grid, and hence the cost of transfer, should be lower. On the other hand, if enough BES systems were all to draw power from the grid when the price of electricity is lower, that could lead to peak demand during those hours, which might force the power company to raise its prices. None of this is a problem yet, but it is something to consider. The demand-side management system would have to be implemented in this situation.

What is clear is that before BES systems become more widely-used in Finland, more and more intermittent renewable energy is going to be installed to the grid. Thus, the patterns for the cost of electricity can be expected to change in such a renewable-energy-influenced market. There will be more frequent occurrences of large variations in electricity prices. Without energy storage systems, the grid's need for reserve peak-power plants will increase, as will the value of BES systems to the consumer.[39]

There are a few other unquantifiable benefits to be gained from BES systems. These include eco-friendliness and the importance of developing new technology. Unless the BES has more capabilities than just the ability to store the excess PV energy for later use, the customer may not appreciate all the benefits a PV-BES system can offer. For example. a home energy management system and smart home integration would easily ramp up the savings to be gained from a state-of-the-art PV-BES.

4.3 Safety of lithium ion battery energy storage systems

When packing large amounts of energy into a small volume, there will always be risks. The risk cannot be completely eliminated, but it can be minimized with good design, high production values, and careful processing and handling. As with gasoline, which is highly flammable but still used daily by most of us, the customer's careful use of lithium ion battery system is important.

The safe performance of lithium ion cells is dependent on both the temperature and the operating voltage. If the charging voltage is increased beyond the recommended upper cell voltage (typically around 4.2 V), excess current flows give rise to two problems. The first is lithium plating, which happens when the lithium ions cannot be accommodated quickly enough between the intercalation layers of the negative electrode, so they accumulate on the surface of the electrode in the form of metallic lithium. This reduces the number of free lithium ions, hence capacity loss. A more serious problem happens when lithium plating causes dendrites to form, which will ultimately result in a short circuit between the electrodes. Lithium plating can also occur when a lithium-ion battery is used at low temperatures.

It is not just overcharging, but over-discharging, which can also cause serious problems. Under-voltage (around 2 V) can occur if the battery lacks a battery management system or the battery modules are not used for a long period of time. Over-discharge causes progressive breakdown of the electrode materials, and can, ultimately also result in short circuiting or capacity loss.

Lithium ion batteries are sensitive to temperature variations. At low temperatures, lithium plating can occur because the cold reduces the reaction rate and makes it more difficult for the lithium ions to penetrate the intercalation layers. This results in lower capacity and lower charging and discharging current in lower temperatures.

Using lithium-ion batteries in high temperatures can cause more serious problems, which can result in the destruction of the cell. Higher power can be drawn at higher temperatures because of the increased rate of the chemical reactions. This means higher currents, which require higher heat dissipation (I^2R), causing still higher temperatures. If this heat cannot be removed faster than it is generated, this will result in thermal runaway.

Thermal runaway is the phenomenon in which the lithium ion battery overheats with destructive force; not something one would want to happen in a residential setting. Figure 25 shows different thermal runaway temperatures for different kinds of lithium ion chemistries.

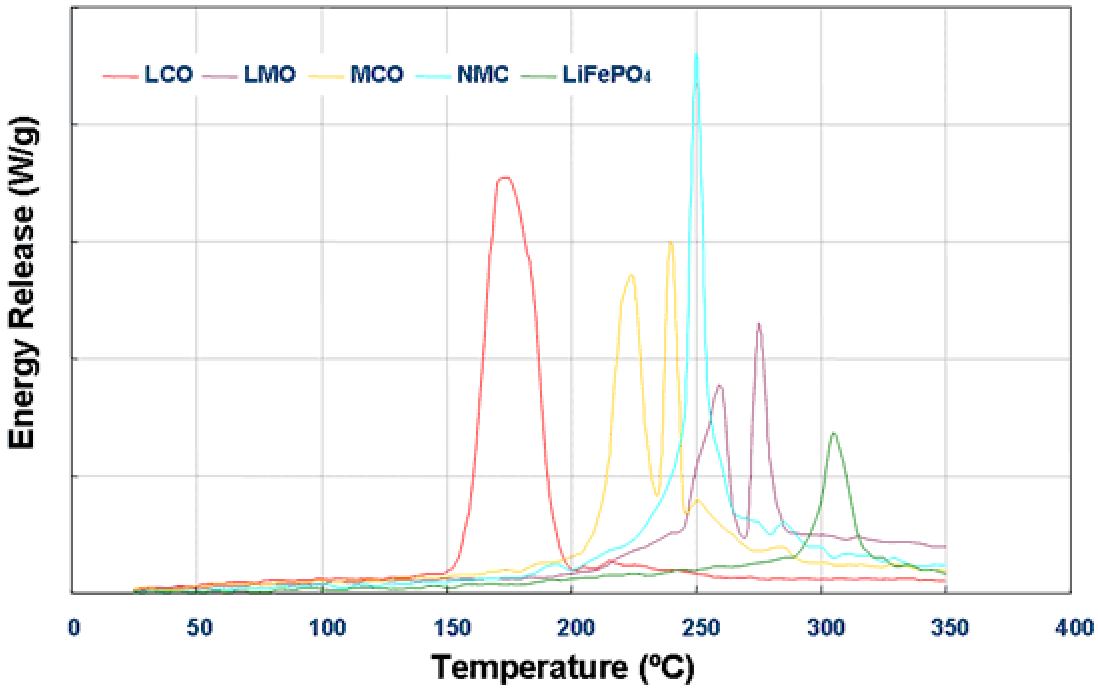

Figure 25. *Thermal runaway temperatures for lithium ion chemistries [40].*

As can be seen from the figure, lithium iron phosphate ($LiFePO_4$) batteries have the highest thermal runaway temperature point, at over 300 ^{0} C. This indicates that they have the most stable and safest chemistry, in addition to which they have the lowest level of energy release during thermal runaway. This is because the oxygen molecules in the phosphate material have much stronger valence bonds with the phosphorus, which are more difficult to break. Therefore, battery energy storage systems with lithium iron phosphate batteries are recommended as a new product offering for Naps Solar Systems.

In production and design, cell manufacturers and battery assemblers can improve the system's safety by choosing the right chemistry, designing the cell correctly and maintaining high production values. The battery management system also has to be designed correctly, and different kind of fuses or pressure valves can be used.

A lithium-ion BES also requires careful handling and use. For example, the batteries can be damaged during transportation, so the installer has to look for any possible damage to the battery modules before installation, and if there is any damage, then the battery has to be replaced. An example of careful use is that battery energy storage systems often have air vents for cooling, and these have to be kept open and must not be covered.

5. ASPECTS AFFECTING THE PROFITABILITY OF PV-BES SYSTEMS

There are many aspects affecting the profitability of PV-BES systems. The savings, and thus the profitability of a PV-BES system for a residential customer is that it allows the customer to buy less energy from the grid. The difference between the quantity of electricity a customer uses when they have a PV-BES, and the quantity they would have used without one, is the key metric. In this regard, fluctuations in the price of electricity, and possible future developments in electricity generation will have a significant impact on the profitability of the system. In this study, the PV-BES system's profitability will be analyzed with a lifetime of 30 years, so it is difficult to accurately predict the electricity price over such a long period. However, this chapter will try to predict the development of the electricity price by analysing previous data, and this predicted price escalation will later be used in the simulations.

We will first look at the demand for electricity, and how it is affected by seasonal and daily variations. In addition, we will look at the factors which contribute to the price of electricity, and how they are formed. Section 5.3 examines the incentives there are in Finland for using a PV-BES system, while section 5.4 reviews how PV-BES systems could be used in the future as part of a Smart Grid, in which they can be utilized for demand-side management. The chapter also describes the methods used in the simulations to calculate the profitability of a PV-BES system.

5.1 Residential electricity demand in Finland

At the end of 2011, there were 2 556 000 residential units in Finland. Almost 60% of these units had electric heating, and altogether they consumed a total of 19 237 GWh of electricity per year. This work focuses mainly on detached and semi-detached houses, of which Finland had 1,035,524 in 2011. These customers used a total of 14 216 GWh of electricity, and 66% of their consumption went on heating the residence, while the remaining 34% supplied the other needs. [41] Figure 26 shows the average electricity consumption for various purposes in detached and semi-detached houses in 2011.

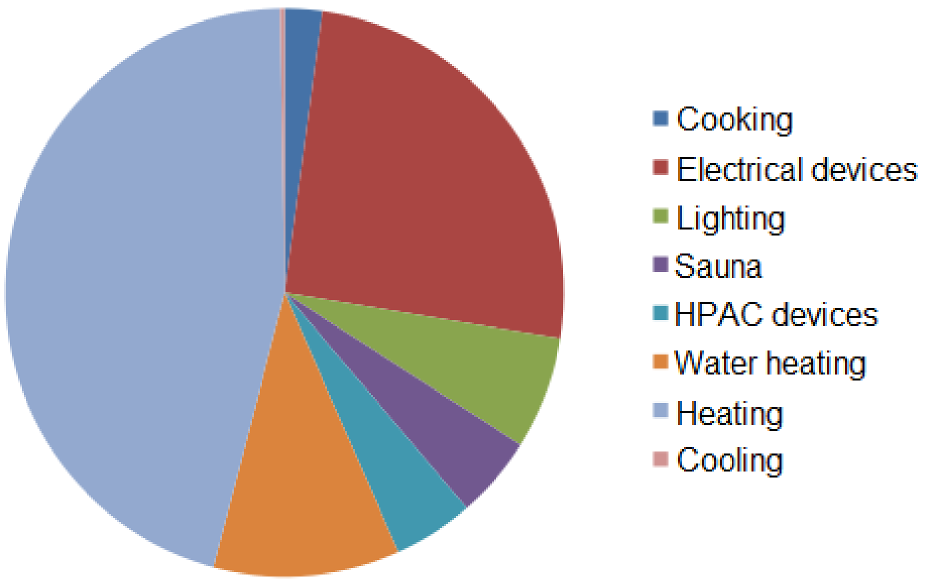

Figure 26. *Electricity consumption in detached and semi-detached houses. Adapted from [38].*

On average, one detached or semi-detached house consumes around 37,6 kWh/d of electricity, and the average power consumption is 1,57 kW. These figures can be used as a rough guide when sizing a battery energy storage system. However, residential electricity consumption is not stable, and it fluctuates considerably depending on the time of day and the season.

These average figures can also account for different heating sources. If direct or indirect electrical heating is used, electricity consumption is 1,44 kWh/h higher than with other heating methods. This means that a detached house with electric heating consumes an average of 2,38 kWh/h of electricity, while a house with some other form of heating only consumes 0,94 kWh/h. [41]

5.1.1 Seasonal and daily variations

Because the power needed for electric heating accounts for such a large portion of the residential customer's total electricity consumption, the weather can have a significant impact on consumption. Heating needs change, depending on the temperature. One recent study has shown that a 1°C change in temperature can affect electricity consumption by approximately 4 %. [38] However, the passive heating from solar radiance and the cooling effect of the wind may cause some error to this correlation, as do insulation and other factors affecting the thermodynamics of the house. Nevertheless, there is no doubt that the ambient temperature is the most significant factor in any calculation of heating electricity consumption.

In Finland, as in any northern climate, electricity consumption is highest in the winter and lowest in the summer. Figure 27 shows the electricity consumption for one detached house over one year. This house is equipped with direct electric heating and water heating.

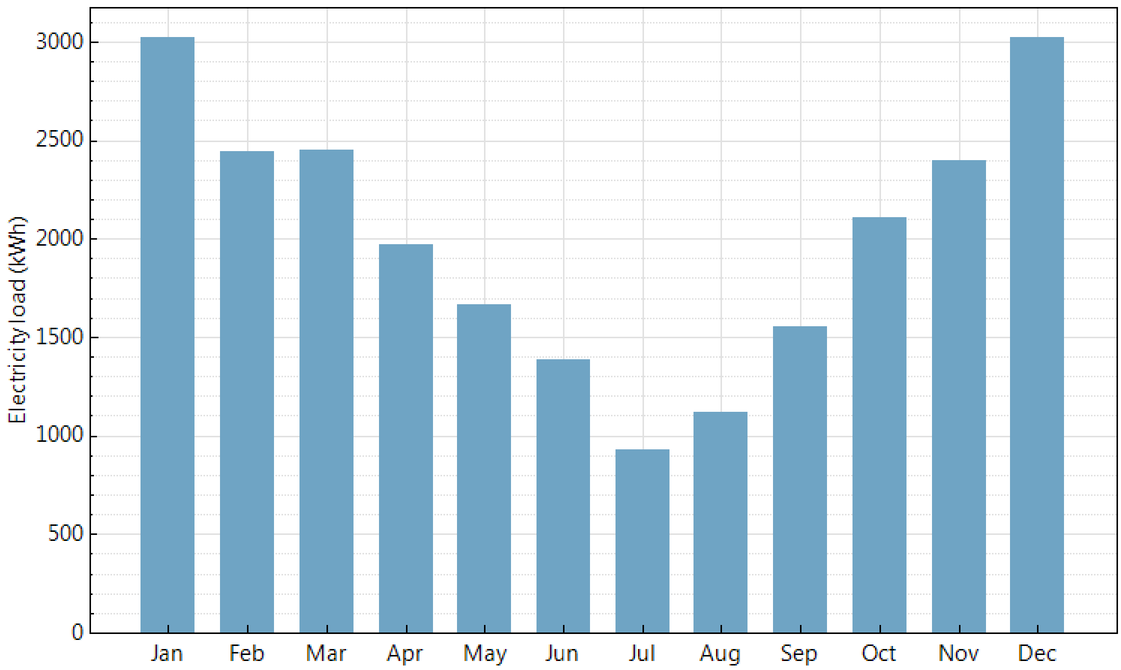

Figure 27. *Consumption of electricity in one year*

Daily fluctuations in the temperature can also have a significant impact on electricity consumption, and ultimately on the amount of electrical energy that can be stored in a BES. On a clear day in spring, the temperature can change by up to 20 °C in a single day. On a cloudy day, the fluctuations in temperature are smaller, around 5 °C, and fluctuations are smallest in midwinter. Typically, temperature fluctuations are greatest in spring and autumn, and during these seasons, the demand for heating power can fluctuate wildly in a single day. [38]

Figure 28 illustrates the difference in electricity consumption for two domestic houses; one with and one without electric heating. The data represents one week in May, 2014 (with electric heating) and May, 2016 (without electric heating). Both houses are roughly the same size and are occupied by similar-size families. It is clear that without electric heating, the consumption of electricity is significantly lower. The house with electric heating has much higher peaks due to water heating at night. If most of the customer's electricity consumption already occurs at night, then this reduces the benefits of time-of-use-shifting.

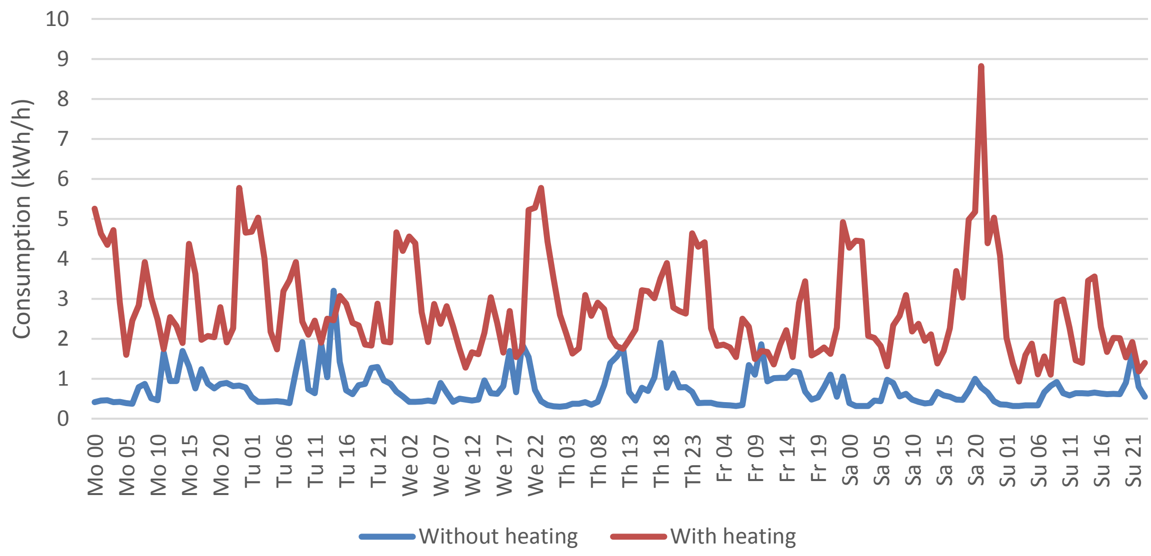

Figure 28. *Comparison of same size residential houses with and without electric heating.*

In houses without electric heating, the daily fluctuation in electricity demand is usually quite predictable. Residential customers tend to use most of their electricity in the mornings and evenings. At mid-day, when the PV production would be highest, the customers do not actually use much electricity. An example of energy consumption in a typical Finnish house over one weekday is illustrated in Figure 29.

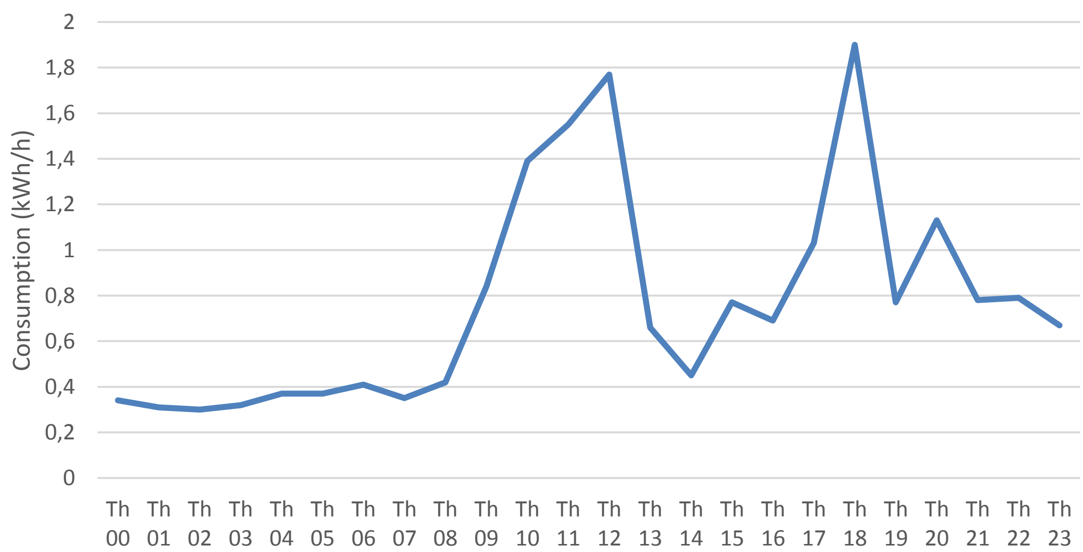

Figure 29. *Example of energy consumption of Finnish residential user.*

At the weekends, energy consumption is usually more stable and higher than it is during the week. In Finland, many urban residences have electric saunas, which are usually heated at the weekends, and this increases energy consumption on a Friday or Saturday evening.

5.2 Electricity price in Finland

The electricity price for a residential customer comprises three factors: electricity transfer (main grid, regional grid and distribution grid), electrical energy (production and sales) and taxation (tax on electricity and value added tax). Figure 30 shows an example of the factors which form the electricity price.

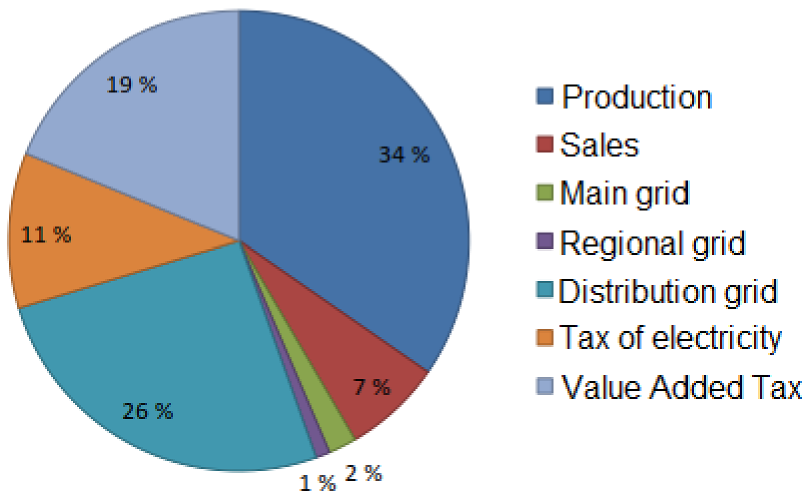

Figure 30. *Formation of electricity price of residential customer. Adapted from [38].*

The cost of electricity transfer can be divided into three different categories: main grid, regional grid transfer and distribution. The distribution grid operator takes the biggest cut from the residential customer. The price of the electrical energy itself is divided into electricity production and sales. In addition, almost one third of the price comes from taxation. Distribution companies have a local monopoly, which means that the customer cannot shop around for their electricity transfer. The only way customers can affect the transfer fee is by their consumption and their choice of tariff. However, customers can choose their electric energy company, so in that way it's possible to make some choices.

Both the transfer fee and the energy fee have fixed (€/month) part of the price and the variation in customers' bills comes from the amount of electricity consumed (€/kWh), which also determines the amount of tax the customer must pay.

5.2.1 Transfer prices

The transfer fee comprises the fixed price for the month (€/month) and the amount of electricity consumed (€/kWh). General and time-of-use pricing are the most common transfer tariffs available today. A general tariff is only dependent on the fuse size, which ultimately means how much power the customer could draw from the grid in any given time. The time tariff has two different fees: daytime and night time. This is most commonly used in houses where there is a thermal storage heating system (indirect electric heating and/or water heating). This kind of tariff could also be used with a BES system, so that the battery can be charged from the grid at night, and discharged, i.e. used, in the daytime.

The tariffs are problematic because they do not encourage customers to use electricity optimally from the perspective of the transfer company. A general tariff doesn't really encourage the average customer to modify their electricity consumption. However, a BES allows the customers to do peak shaving, and if they could manage with smaller fuses, then their electricity bills would be significantly lower. The problem with time-of-use -pricing is that every night all of the thermal storage heating systems connect to the grid at the same time, which causes another peak demand for the transfer grid.

New tariff mechanisms are likely to be introduced in the future. Their main purpose will be to restrict power peaks by encouraging customers towards more stable energy use. From the customer's point of view, having their own PV-BES system would do just that. If more residential customers had PV-BES systems, that would have a significant impact on conventional energy production and the need for reserve power. For example, the national grid would not need to be constructed with so much reserve capacity.

One possible transfer tariff that has been suggested would be based only on power, and it would be one single fixed price (€/month). This would encourage customers with a PV-BES to do peak shaving, but it wouldn't encourage them to become producers, and neither would it encourage them to become more energy-efficient. Such a tariff would reduce the profitability of a PV system.

5.2.2 Electric energy prices

Customers can freely shop around for their electrical energy. This price is comprised of a monthly fee (€/month), the energy fee (€/kWh) and the pricing model used. Energy companies usually offer open-term contracts, so the company can change its prices at certain intervals, but these contracts also allow the customer to change his energy supplier whenever he wants. Fixed-term contracts, in which the supplier fixes its prices at a certain level and the customer commits to fulfilling the contract until its due date, are becoming more popular.

Following the recent development of remote reading ARM-meters, it is nowadays possible to get a contract that follows the market prices every hour. In this kind of contract, the price of the electricity is based on a common Nordic market price, although the energy company also has its own profit margins. This pricing model encourages customer to use electricity when the price is at its lowest point, thus encouraging peak shaving and time-of-use -shifting. A customer using this kind of pricing model would be wise to invest in a smart home control system and a BES.

5.2.3 Formation of market prices

In this thesis, the electricity market price means the local Finnish price on the common Nordic market (the Nord Pool Elspot-market). The Elspot-market sets the spot price for electricity one day ahead for every hour, and is based on the laws of supply and demand. Electricity 'buy' and 'sell' offers include the price and the quantity, and supply and demand curves can be formed using this data. The hourly price is determined by the intersection point of these two curves, as illustrated in Figure 31.

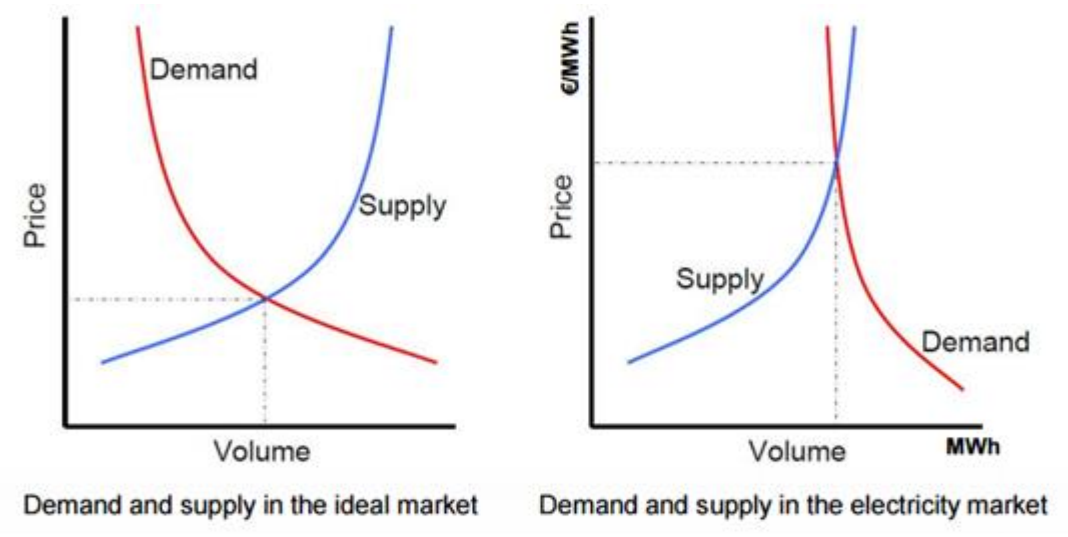

Figure 31. *Formation of Elspot-price*

The Finnish local price might not be exactly the same as the Elspot-price because there are certain transfer restrictions which can disturb the free market. For example, although there may be plenty of cheap hydro-electric power from Norway or Sweden on offer, only a specified amount of that power can be transferred to Finland. If the demand in Finland is not met, the Finnish local price will be higher because the Finnish grid would need to satisfy the required demand for power with more expensive sources of energy. All the spot price contracts offered in Finland are based on this Finnish local Elspot-price.

5.2.4 Current electricity price, and the escalation rate

The average prices of electricity over the past decade will be used to determine the price escalation of electricity. As can be seen from Figure 32, the average electricity price in Finland has risen steadily since 2006.

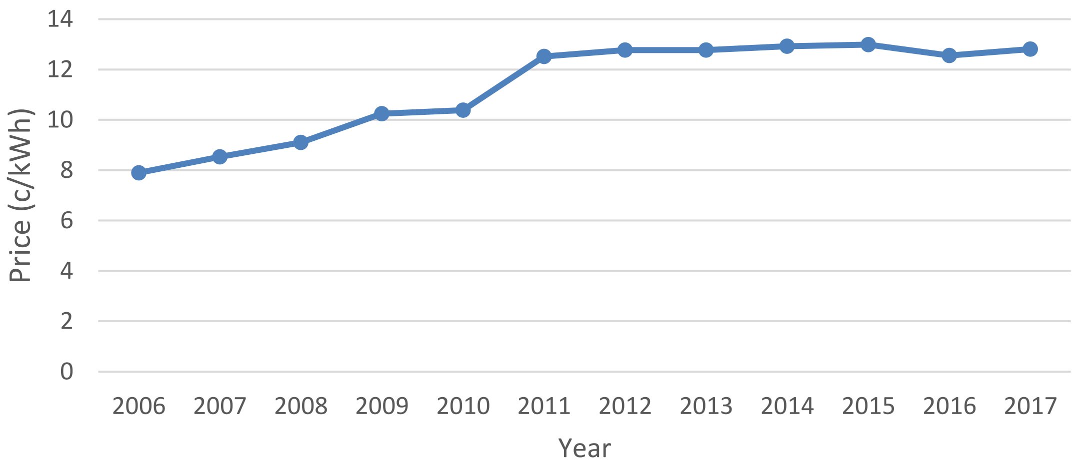

Figure 32. *Electricity prices from start of 2006 to the end of 2016 (includes transfer, energy and taxes). Adapted from [42].*

The average electricity price at the beginning of 2006 was 7.9 c/kWh. By the end of 2016, this had risen to 12.81 c/kWh. This data shows that the escalation rate of the price of electricity price is 3.8 %/a, which is the rate that will be used later in the simulations.

The case study customer in Helsinki has Fortum as his energy company, and Caruna as his transfer company. These companies' publicly available price information is used for the simulations, and are shown in Table 6.

Table 6. *Price information [43; 44]*

	Daytime (c/kWh)	**Nighttime (c/kWh)**	**Fixed (€/month)**
Energy	6.9	5.95	4.02
Transfer	3.08	1.83	12.95
Taxes	2.79	2.79	
Total	**12.77**	**10.57**	**16.97**

The prices are for a time-of-use-tariff. The total daytime price is 12.77 c/kWh and the nighttime price is 10.57 c/kWh. These prices include value added tax (VAT). A fixed charge of 16.95 €/month is also paid every month.

5.3 Political factors and incentives

The Finnish Ministry of Economic Affairs and Employment has decided to give 25 % investment support to industrial and commercial customers who invest in the small-scale production of renewable energy, which includes photovoltaics. This financial support is not available to domestic consumers, but is only given to public organizations, companies or municipalities which invest in projects that are climate and environmentally friendly. [45]

Although residential customers cannot get this investment support, they do get a tax credit for investment in a PV-BES system. This tax deduction is 50 % of the cost of any work done to install the system (VAT included). This tax credit cannot be claimed on the cost of the devices, or transportation, but only for the labour. Excess deduction is 100 € and the maximum tax credit is 2400 €/person. The tax credit is per person, so with two partners living in the same household, the maximum tax credit could be 4800 €, although the excess deduction is taken from both claimants. [46] According to [20], the tax credit for a domestic customer who invests in a PV system is usually around 14-18 % of the total cost. Therefore, an average of figure of 16 % is used in the simulations, which will take this tax credit into account.

5.4 The Smart Grid and the Smart Home

The national grid has traditionally been a one-way street for electricity. The grid transfers power from large centralized generators to a wide-area network of customers. The traditional grid supports four operations: electricity generation, transmission, distribution and control. The Smart Grid is the next step in the evolution of the traditional grid. The Smart Grid's operation is based on two-way flows of electricity and information, which create an advanced, automated and distributed energy delivery network. A comparison between a traditional grid and a Smart Grid is shown in Table 7.

Table 7. *Traditional power grid vs. Smart Grid. Adapted from [47].*

Existing Grid	**Smart Grid**
Electromechanical	Digital
One-way communication	Two-way communication
Centralized Generation	Distributed Generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

As can be seen from the table, most of the differences between the traditional grid and the Smart Grid come from the implementation of information technology into the traditional grid. An Advanced Metering Infrastructure (AMI) is the first step needed towards the implementation of a Smart Grid. This has already started in Finland, and some Smart Grid capabilities have already been enabled with these new electricity meters. The other vital thing for a Smart Grid is the full implementation of distributed generation.

In the electricity industry, production has traditionally followed demand. However, a Smart Grid would be able to make demand follow production. This could be achieved through demand-side management, which will become an increasingly important aspect of the Smart Grid when more intermittent renewable energy sources are connected to the grid. Demand-side management can be linked to, for example, electric heating. Residential electric heating is a good subject for demand-side management, because it can be turned on or off at the flick of a switch, but turning the heating off for an hour or two in a domestic residence won't make a huge difference to room temperatures in the residence. Thus, the heating in a house could be turned on when PV production is at its highest point (or the price is lower). Battery energy systems could also be worthwhile subjects for demand-side management. The grid could charge and discharge these systems when power is needed elsewhere, or when there is surplus power which needs to be balanced somehow.

The Smart Home can be regarded as one part or entity in a Smart Grid. The Smart Home would include self-monitoring, advanced metering, demand-side management and peak shaving capabilities. Investing in a battery energy storage system would include some of these features, so it is one step towards the customer's house becoming a Smart Home. Most PV-BES systems are already capable of metering production and demand, and of storing the electricity through intelligent optimization of the system. Some the battery systems can already contribute to demand-side management and to peak shaving. Most of the systems are capable of metering the production, demand and storing of electricity and intelligently optimizing the use of the system.

At the moment, there are no direct incentives for converting to a Smart Home or contributing to demand-side management. However, with the right incentives, customers could well see the benefits of having a Smart Home in the future, and installing a BES would be more profitable than it is at present.

5.5 Profitability calculation methods

The profitability of the BES system is analyzed with three different profitability calculations: the payback period, the net present value and the internal rate of interest methods. All of these methods need an estimate of how much solar power is stored in the batteries for later use, and also how much money the system will save because of time-of-use – shifting. These methods are all subject to variations in electricity costs, which are difficult to forecast, and they do not account for anything other than the monetary benefits of the BES.

The payback-period method is the most imprecise of the three. This method determines the time it will take before the investment cost is covered from the net yields. It only accounts for the initial investment and possible maintenance costs of the system, and the price of the saved electricity is subtracted from this. Payback period as calculated with

$$Payback\ period = \frac{Investment\ cost}{Cash\ inflow\ per\ year}\ . \tag{5.1}$$

Formula 5.1, is suitable only if the cash flows are even for every year. If they are uneven, one needs to calculate the cumulative net cash flow for each year, and then calculate

$$Payback\ period = A + \frac{B}{C} \quad (5.2)$$

where *A* is the last year with a negative cumulative cash flow, *B* is the absolute value of the cumulative cash flow at the end of year *A*, and *C* is the total cash flow during the year after *A*. The payback period method does not take into account the time value of money, nor the cash flows after the payback period. Because of this, the payback period is poorly suited for this kind of profitability calculation, so it is only used for rough estimates. The longer the payback period, the poorer the investment. If the net yields are not enough for the payback point to occur in the system's designed lifetime, the investment will definitely be unprofitable.

The net present value method is a more sophisticated way of calculating the profitability of a BES system. This method takes into account all the income and expenses of the system in its lifetime, and all of the net cash flows are converted into current values. The net present value is calculated from

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad (5.3)$$

where C_t is net cash inflow during the year, C_0 is total investment costs, *r* is the discount rate and *t* is the number of years. The investment is profitable if the net present value is positive. The chosen discount rate also has an impact on this method. With a discount rate of 0 %, the method will not take into account the time value of money, but with a discount rate of 1 % it matches the inflation rate. [48] Only the inflation rate is considered in the simulations, leaving the internal rate of interest method to be used for even more precise profitability calculations.

The internal rate of return is calculated using formula 5.3. The net present value is set to zero and one needs to solve the discount rate, *r*. The investment is profitable if the internal rate is greater than the expected profit rate of the system. The expected profit rate could be interest on a loan or the profit from other investment options.

5.6 Monetary benefits of PV-BES system

The monetary benefits of a PV-BES system will be analyzed in Chapter 6 through simulations. The benefits of the PV-BES system can easily be calculated from the savings in electricity bills. Excess energy, which the customer has no use for, will be sold at a specified price, made up of the market price minus the energy supplier's profit margin. Usually, it is more profitable for the customer to use his own PV electricity than to sell it to the grid.

The monetary benefits of a BES are drawn from two different sources in the simulations: the excess PV energy production which the customers can use themselves (instead of selling it to the grid at a lower price than it would cost to buy) and time-of-use –shifting.

As much as possible of the excess energy produced by the PV modules is stored in the BES. If the batteries are fully charged, or the BES system is already charging at its highest rate, then the excess energy from the PV system will be sold to the energy company for the same price as is used in the simulations for a house which only has a PV system. The batteries are discharged when the price of electricity is high and the PV production cannot meet the customer's demand. As it is more profitable for the customer to use his own stored energy, rather than selling it to the grid, this is how the monetary benefits are calculated. However, there are some energy losses in any BES system, and these need to be taken into account, as they reduce the profits.

Variations in the electricity price give rise to another monetary benefit of a BES. This is based on the capability of the BES to draw energy from the grid when the prices are low, and then the stored energy can be discharged when the prices are high. The benefits of this kind of TOU–shifting comes from the difference between the lowest and highest prices for electricity from the grid. Once again, though, the BES system's own energy losses need to be taken into account.

6. CASE STUDY: RESIDENTIAL PV-BES SYSTEM

For this case study the chosen battery energy storage system is installed for a customer near Helsinki Finland in a detached house. The customer's house is already equipped with 1.5 kW_p photovoltaic system. The objective of the simulations is to analyse the potential profitability if the customer were to add a BES to his existing PV system. The methodology is to analyse the profitability of the PV system as it is, without a BES, and then to compare this with the same system with a BES. The first simulations are performed with the installed PV system (1.5 kW_p,), after which the BES system can be sized according to the results of these simulations. After this, the same simulations are performed with 3.5 kW_p, 7 kW_p and 10.7 kW_p PV systems.

The house is 130 m^2 with an additional 30 m^2 of storage space. There are six persons in the household, and the annual electricity consumption is around 24 000 kWh. The house is equipped with electric space and water heating. The data used in the simulations includes information about the hourly electricity consumption of the house. The data is taken from the year before the installation of the PV system, i.e. from 1.5.2014-30.4.2015, and includes 8760 data points. An example of the weekly consumption for July is illustrated in Figure 33.

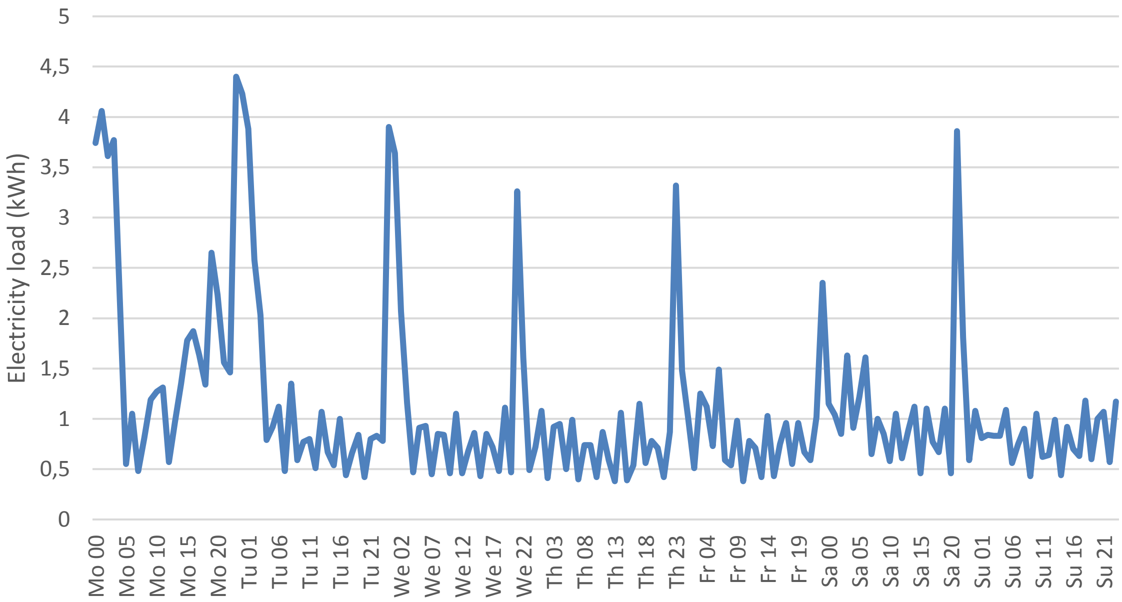

Figure 33. *Example of weekly consumption in July*

Peak consumption in the sample is 4,4 kWh/h, and the lowest consumption is 0.4 kWh/h. The peaks in electricity consumption mainly come from the electrical heating of water. These peaks already occur in the nighttime, which means that the profitability of the BES system could be even greater in a house with another method of heating. For this reason, the study also makes a comparison with a similar residential house without electric heating. The consumption patterns in the wintertime are less interesting because the PV system does not produce much energy then.

The annual variations in electricity consumption are illustrated in Figure 34. Naturally, as with any house in a northern climate, the highest consumption is in winter, and the lowest in summer. The electric heating system means that the outside temperature has a significant effect on the electricity demand.

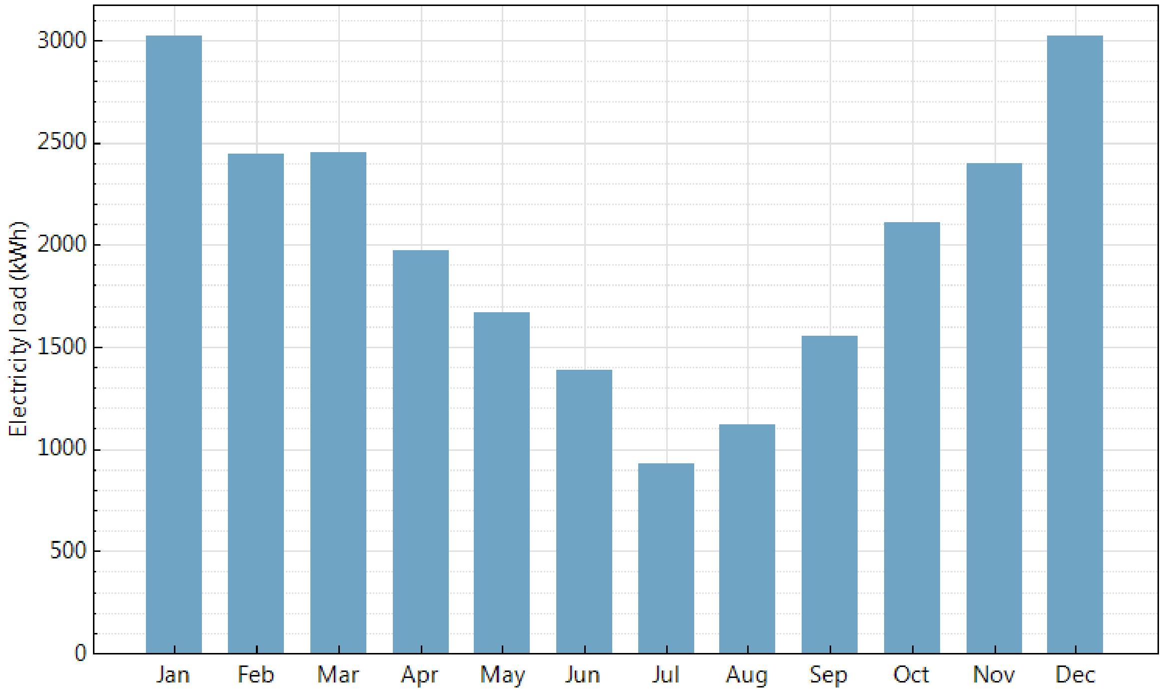

Figure 34. *Monthly electricity load.*

Although the annual energy yield from a PV system is almost as high as it is, for example, in Germany, in Finland the energy yield fluctuates greatly between the summer and the winter months. The highest electricity production for the PV is achieved in summer time, when the required consumption is at its lowest point, and vice versa. This can have a significant impact if the PV system is oversized, as much of the excess energy must be sold to the grid, rather than used by the customer himself. Hence, the profitability of the BES system could be higher, although the profitability of PV systems in Finland is generally lower than in Germany.

6.1 Simulation model and input data

The simulations were done with the System Advisor Model (SAM) version 2017.1.17. SAM is a performance and financial model specifically designed to facilitate decision-making for people involved in the renewable energy industry. SAM makes performance predictions and cost-of-energy estimates for grid-connected power projects based on the installation and operating costs and the system design parameters, which are specified as inputs by the user. SAM has been developed by the National Renewable Energy Laboratory (NREL) with funds from the U.S Department of Energy. SAM collaborates with Sandia National Laboratories for the photovoltaic models. [49]

SAM includes weather data for Helsinki and Tampere. This data is from the International Weather for Energy Calculations (IWEC). The IWEC are the result of ASHRAE Research Project 1015. This was conducted by Numerical Logics and Bodycote Materials Testing, Canada, who carried out the work for the ASHRAE Technical Committee 4.2 Weather Information. The IWEC data files are 'typical' weather files suitable for use with energy simulation programs for 227 locations outside the USA and Canada. The files are derived from up to 18 years of DATSAV3 hourly weather data, originally archived at the U. S. National Climatic Data Center (1982-1999 for most stations). The weather data is supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly data about the amount of cloud. [49; 50]

The weather data from Helsinki is used for the simulations. The annual average direct solar irradiance is 1.95 kWh/m^2/d and the horizontal diffuse radiation is 1.55 kWh/m^2/d. The average temperature is 5.2 °C and the average wind speed is 3.8 m/s. The energy production of a 3.5 kW PV system with this irradiance data is illustrated in Figure 35.

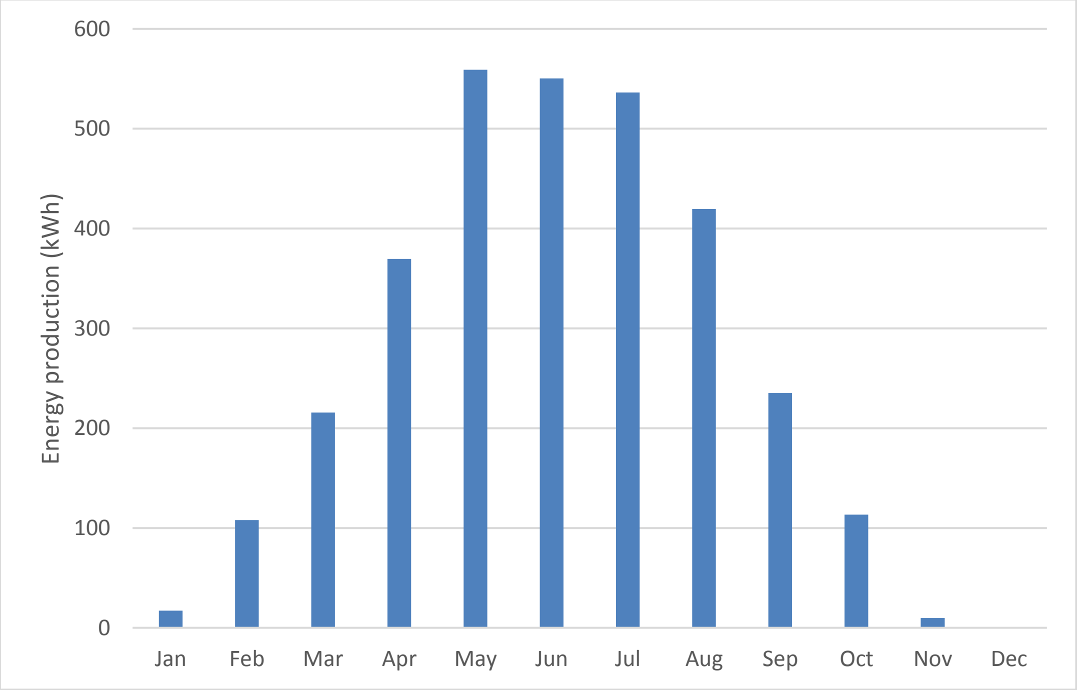

Figure 35. *Monthly PV production of 3.5 kW system*

The inclination is fixed at 20 degrees, and the orientation, or azimuth angle, is 0 degrees. In other words, the system faces south. PV modules used in the simulations are high-efficiency monocrystalline modules with efficiency of 20 %. The total system losses of the PV system are estimated to be approximately 15 %. These losses mostly consist of soiling 2 %, module losses 2 %, module mismatch 2 %, DC wiring 2 %, inverter power consumption 2 %, inverter efficiency 3 % and AC wiring 1 %. The degradation rate of the PV modules is estimated to be 0.5 %/year. Shading has not been taken into account in these simulations. Although shading does have a significant impact on the operation of PV systems, the main idea of this study is to analyze the effect of the battery energy storage system. These simulations may contain some errors because of this assumption, but the results can be more easily used in to compare different PV systems.

The prices for the PV and BES systems used in the simulations are based on confidential information from Naps Solar Systems. They include value added tax (VAT) and standard installation costs. These prices can be seen in Appendix A, (*not to be included in the published version of this thesis*).

The available tax deduction for a domestic customer is taken into account by deducting 16 % from the total investment cost. It is assumed that the inverter needs to be changed after its 15-year lifetime. An analysis period of 30 years is chosen for the simulations, and a 1 %-inflation rate is used in the profitability calculations, which matches the current inflation level. Electricity rates of 12.77 c/kWh and 10.57 c/kWh are used for day and night respectively. In addition, 16.97 €/month is used for the fixed tariff. [43; 44]. The selling price for the excess PV energy is estimated to be 3 c/kWh. The electricity bill escalation rate is taken to be 3.8 %/a.

6.2 Technical details of the chosen product

One of the primary objectives of this thesis was to make a techno-economic comparison of different battery technologies. The ultimate result of this comparison was that lithium iron phosphate technology would be the best choice for a residential BES system installed in parallel with a PV system. The most promising topology was considered to be a BES system coupled to the AC side with its own inverter, because of its versatility. It is anticipated that many of these BES systems will be sold to existing PV customers, and with this kind of topology the BES system can be sized optimally while the PV system doesn't need to be touched.

Because of the above considerations, a battery energy storage system with these features was selected for the study. In fact, Naps Solar Systems has already started negotiations with a BES manufacturer which offers this kind of solution. The chosen BES system is the sonnenBatterie eco 8.0, as shown in Figure 36.

Figure 36. *sonnenBatterie eco 8.0 [51].*

This BES can be sized from 4 kWh of capacity to 16 kWh of capacity in increments of 2 kWh. All the relevant technical details are shown in Table 8. Thousands of sonnenBatteries have been installed globally, and the company is the global market leader in battery energy storages.

Table 8. *Technical details of sonnenBatterie eco 8.0. Adapted from [52].*

Capacity (kWh)	**4.0**	**6.0**	**8.0**	**10.0**	**12.0**	**14.0**	**16.0**
Ambient temperature (°C)	5-30						
Battery service life	20 years						
Warranty	10 years						
Cycles	10 000						
Nominal power (W)	2500	3000	3300	3300	3300	3300	3300
Small cabinet (4-10 kWh)							
Weight (kg)	96	121	146	171	-	-	-
Dimension (H/W/D cm)	137/64/22	137/64/22	137/64/22	137/64/22	-	-	-
Big cabinet (4-16 kWh)							
Weight (kg)	107	132	157	182	207	232	257
Dimension (H/W/D cm)	184/64/22	184/64/22	184/64/22	184/64/22	184/64/22	184/64/22	184/64/22

The product uses 2 kWh lithium iron phosphate battery modules from Sony. The system's maximum nominal power is 3.3 kW, but in the 4 kWh and 6 kWh versions the nominal power is limited to 2.5 kW and 3 kW respectively. The system has a warranty of 10 years on all parts. The cycle life is estimated to be 10 000 cycles. The ideal ambient temperature needs to be between 5 and 40 °C, so it is recommended that the batteries be installed indoors, at room temperature. The system includes an inverter, so it can be installed in parallel with an existing PV system. In addition to the battery modules and the inverter, the system includes an intelligent energy manager, measurement technology and the software to operate the system optimally. All of this is installed in a single casing, the size of the cabinet being dependent on the number of battery modules included. A maximum of three 16 kWh battery systems could be installed in parallel to each other, increasing the maximum capacity to 48 kWh. The simulations on the operation and profitability of the battery energy storage is done using the information from the sonnenBatterie eco 8.0.

The Naps marketing material (Naps KotiAkku™) was produced in Finnish by colleagues at Naps Solar Systems, and some of the information from this thesis was used in that material.

6.3 Operation and sizing of PV-BES System

The chosen product can be sized from 4 kWh to 16 kWh in increments of 2 kWh. Sizing is done with the help of the simulation model, keeping in mind that the amount of PV excess energy sold to the grid should be smaller than that used to charge the BES.

Because the house only has a 1.5 kW PV system, even without the BES system not much of the solar power is sold to the grid. Therefore, the smallest BES system (4 kWh) was chosen for this case study, and for the installation of the demo system.

As can be seen from Figure 37, the battery system is used mostly for TOU-shifting. Every night, the system charges itself from the grid and uses the stored energy later, when it is needed. The results indicate that a 1.5 kW PV system is so small, and the load of the residential house so high, that a battery system is not really effective.

In this case, the battery system is only used to store around 10-30 kWh/month of PV energy in the summertime, and no excess solar power need be sold to the grid.

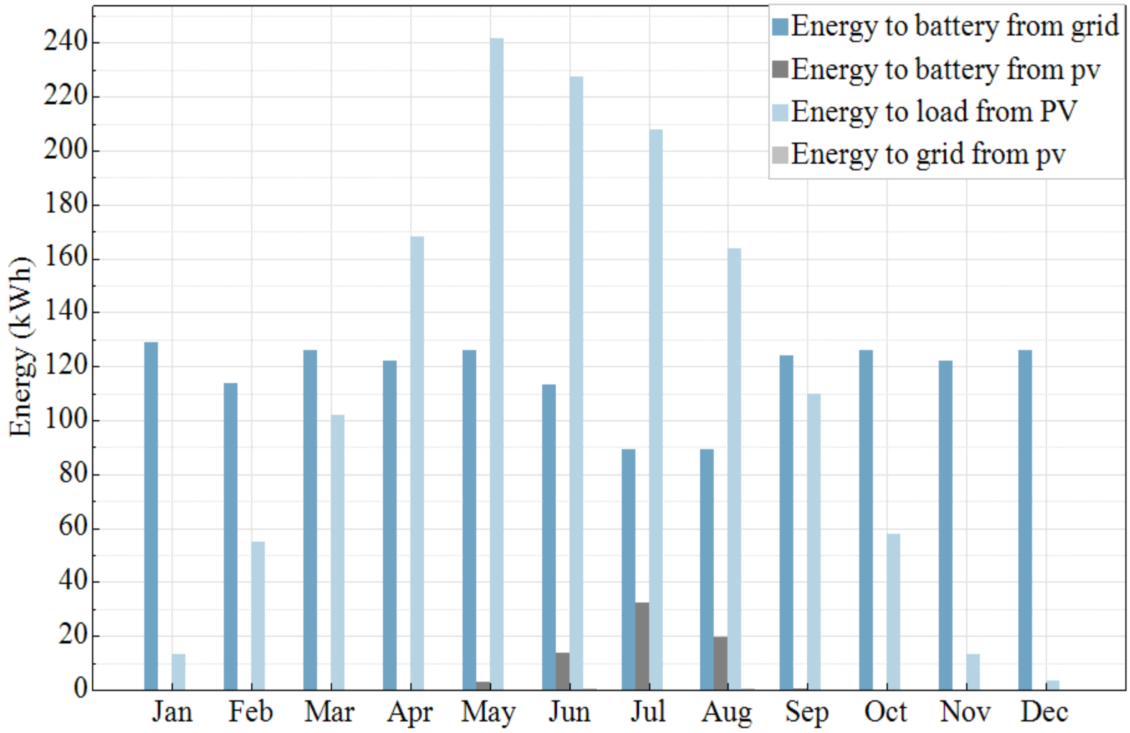

Figure 37. *Operation of 1.5 kW PV and 4 kWh BES system in Finnish residential customer.*

With a 3.5 kW PV system, the benefits of a BES system become clearer. With the house's load, the BES system could be sized anywhere from 4 kWh to a maximum of 10 kWh. Any larger BES system would be pointless because the amount of solar power sold to the grid is quite minimal, even with 10 kWh BES. For these simulations, the 8 kWh BES was chosen.

The next simulation was therefore done with a 3.5 kW PV system attached to an 8 kWh BES system. With this system, it is recommended to charge the BES system from the grid from September to April. The BES system is reserved for PV charging in the summertime. The operation of this PV-BES system is shown in Figure 38.

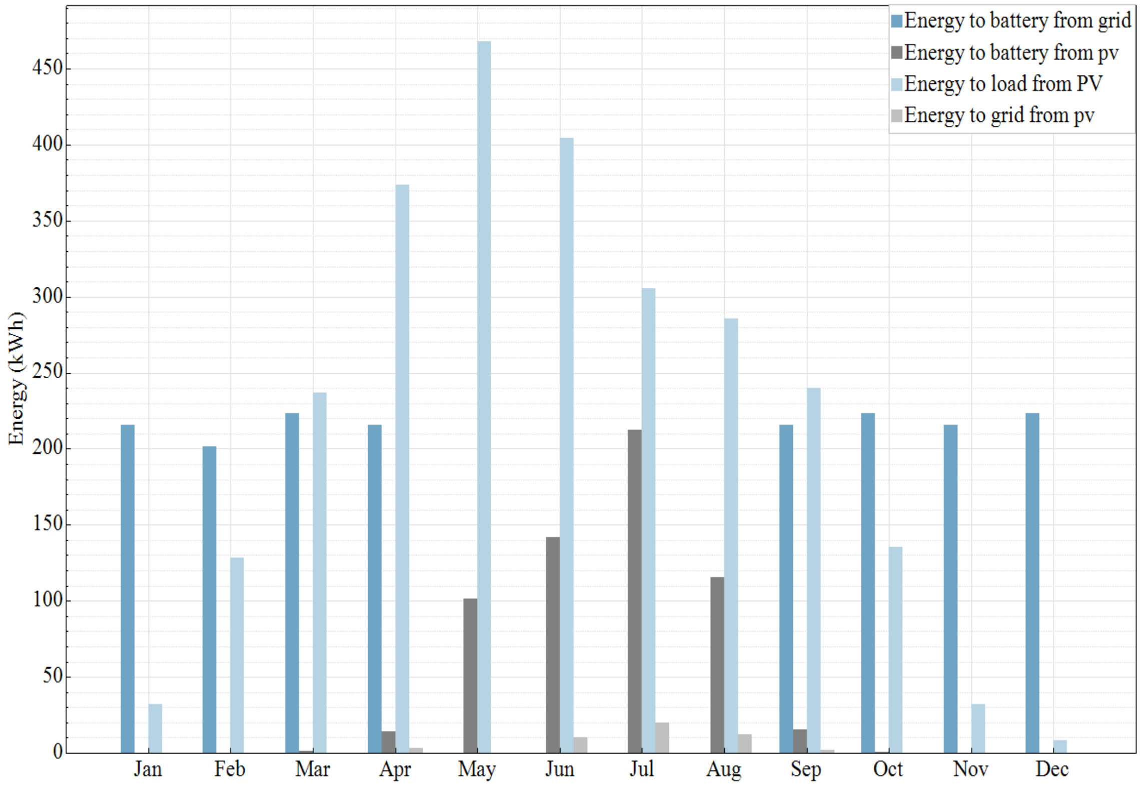

Figure 38. *Operation of 3.5 kW PV and 8 kWh BES system.*

As can be seen from the graph, only 10-30 kWh/month of energy from the PV is sold to the grid in the summer time, so a larger BES system would not be of much use with this size of PV system.

With a 7 kW PV system, the smallest BES systems are not optimal, because too much excess PV energy has to be sold to the grid with the smaller BES systems. Although 10 kWh to 16 kWh BES systems are all capable of handling the excess PV energy, even with the largest system some of the solar power has to be sold off to the grid in the summer months. Therefore, a 12 kWh BES was chosen for the simulations. The charging pattern remains much the same as for the 3.5 kW PV system, as can be seen from Figure 39. With a 7 kW PV system, an even higher-capacity BES system would still be beneficial, as some of the excess PV energy still has to be sold to the grid in summertime.

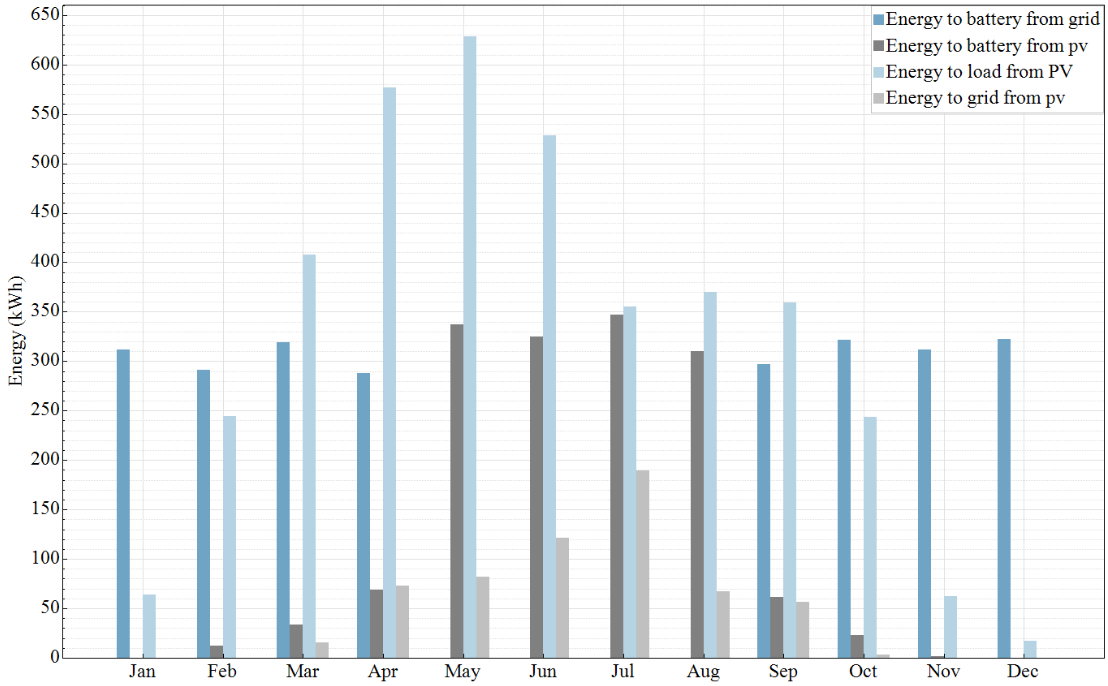

Figure 39. *Operation of 7 kW PV and 12 kWh BES system.*

A 10.7 kW PV system is so large that even with the largest BES system available, a great deal of the solar power still has to be sold to the grid. The 16 kWh BES system was therefore chosen for this comparison. The operation of a 10 kW PV system with 16 kWh battery energy storage can be seen from Figure 40.

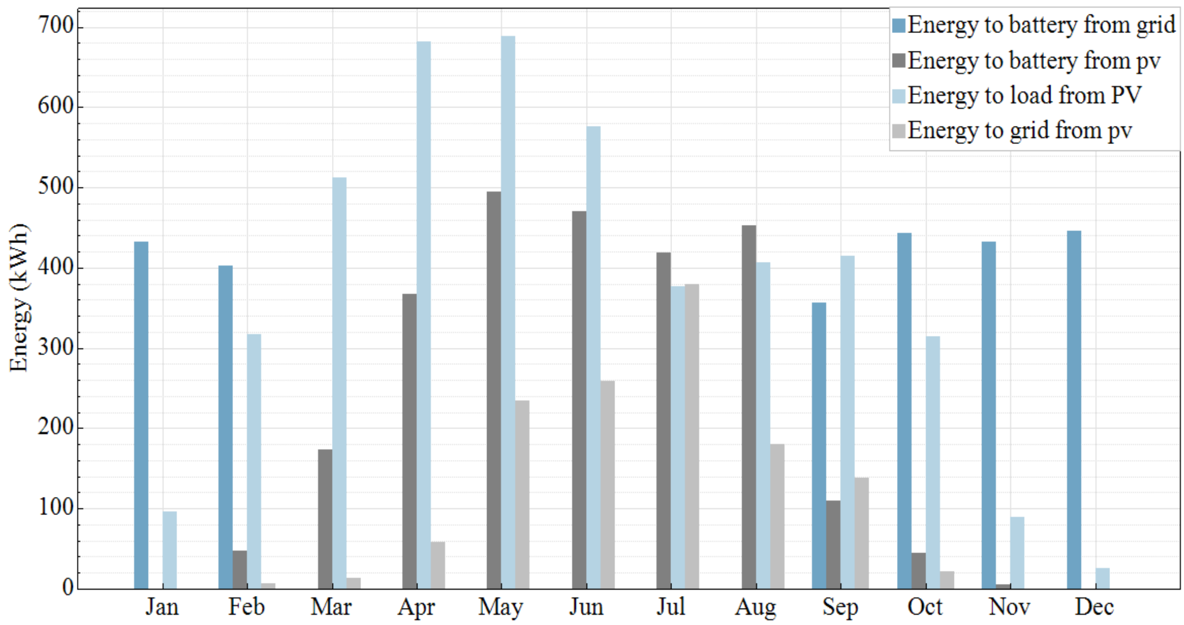

Figure 40. *Operation of 10.7 kW PV and 16 kWh BES system.*

As can be seen, the battery system is only used for TOU-shifting from September to February. From March to August the system is only charged with the excess PV energy.

Nevertheless, the PV system is so large that even with the largest available BES system, a large amount of energy is sold to the grid in the summertime. However, with 16 kWh of battery capacity, more solar power is charged to the battery than is sold to the grid, which is on the right side of the equation for profitability.

It has to be remembered that the sonnenBatterie has a maximum charging and discharging power of 3.3 kW, so with the larger PV systems, this means that some energy is sold to the grid because the BES system is already being charged with highest power possible. This is another reason why a larger-capacity BES system might not make much difference. However, with this BES system it is possible to use demand-side management, to shift the demand to the hours with highest production and this way the maximum power of 3.3 kW would not necessarily be a problem. Demand-side management isn't taken into account in these simulations, although it could have an effect to the operation of the system. Demand-side management would make the larger BES systems more profitable because the PV overproduction would not have to be sold to the grid in so large extent. In addition it could be possible to install slightly smaller BES because the highest demand in the evening could have been shifted to the noon, when the PV production is also the highest.

6.4 Profitability calculations

Profitability calculations are made with these four PV-BES systems based on the results of the simulations. The year 1 electricity bills without the system, with only a PV system and with a full PV-BES system are shown in Table 9. The final column in the table shows is the key one for any customer, as it shows the annual savings that can be achieved if a BES system is attached to a PV system.

Table 9. *Year 1 electricity bill with and without the system.*

PV-BES system	Without system (€/a)	With PV (€/a)	With PV+BES (€/a)	Savings from BES (€/a)
1.5 kW, 4 kWh	3057	2882	2865	17
3.5 kW, 8 kWh	3057	2703	2638	65
7.0 kW, 12 kWh	3057	2489	2353	136
10.7 kW, 16 kWh	3057	2330	2117	213

The monetary benefit to the customer installing a 4 kWh BES system with a 1.5 kW PV system in year 1 would be 17 €/a. This is low, and would not persuade a customer to install a BES system in parallel with such a small PV system. The bigger the PV system, the greater the savings, regardless of the size of the BES. For example, with a 3.5 kW PV system and a 4 kWh BES system, the annual savings are 44 €. With a 7 kW PV system, the same BES would yield 61 €/a.

The profitability calculations are made over a 30-year analysis period with a 1 % discount rate and a 3.8 % p/a escalation rate for the electricity price. The net present value, payback period and the internal rate of interest is calculated for each of the systems, including those with only a PV system. These values are shown in Table 10.

Table 10. *Net present value, payback period and internal rate of interest of PV-BES systems.*

PV-BES/PV only	Net present value (€)	Payback period (years)	Internal rate of interest (%)
1.5 kW, 4 kWh	-3 897	30	-0.70 %
1.5 kW PV	4 183	17.5	5
3.5 kW, 8 kWh	2 133	25.4	1.7
3.5 kW PV	11 825	11.2	9.5
7.0 kW, 12 kWh	7 494	23.4	2.4
7.0 kW PV	17 829	13.3	7.8
10.7 kW, 16 kWh	7 577	24.1	2.2
10.7 kW PV	19 743	15.8	6.5

The net present value of a 1.5 kW PV and a 4 kWh BES system is -3 897 € and it would take more than 30 years to pay for itself, hence the negative internal rate of interest (-0.7%). Without any BES system, the net present value of a 1.5 kW PV system would be 4 183 € and the payback period is 17.5 years. As can be seen from these figures, the BES system is not greatly profitable, so with such small PV systems it is not recommended to install any BES system.

The net present value of a 3.5 kW PV and an 8 kWh BES system is 2 133 € and the payback period is 25.4. The internal rate of interest is 1.7 %, which is only just above the inflation level.

The net present value of a 7 kW PV and a 12 kWh BES system is 7 494 € and the payback period is 23.4 years. The internal rate of interest is 2.4 %, which suggests that the whole system is profitable. Still, the BES system in itself is not profitable because the 7 kW PV system's net present value is 17 829 €, the payback period is 13.3 years and the internal rate of interest is 7.75 %.

The net present value of a 10.7 kW PV and a 16 kWh BES system is 7 577 € and the payback period is 24.1 years. Without the BES system, the net present value of a 10.7 kW PV system would be 19 743 € and the payback period would be 15.8 years. As can be seen from these figures, the BES system is not profitable because the PV system is more profitable on its own than it is with a BES system. However, its worth noting that the 10.7 kW and 7 kW PV systems with optimally sized BES systems have almost the same net present value. This indicate that the large PV systems are not very profitable even with addition of a BES sytem.

The annual savings for a 4 kWh BES system with a 3.5 kW PV system is around 44 €/a with TOU-shifting, and 35 €/a without TOU-shifting. The difference is reflected in the net present values, which are 4 938 € and 4 522 €, so it can be deduced that around 80 % of the benefits of the BES come from its use for storing the excess PV energy, and only 20 % comes from the TOU-shifting.

6.5 The effect of the heating method on the operation and profitability of a PV-BES system

In these simulations, different consumption data were used. This data is from a 200 m^2 semi-detached house in Helsinki with five occupants. The house is heated with district heating, rather than electricity. The annual consumption of grid electricity is only 7674.12 kWh, instead of the 24 000 kWh needed for the electrically-heated house used in the earlier simulations. The residence's monthly electricity consumption is illustrated in Figure 41.

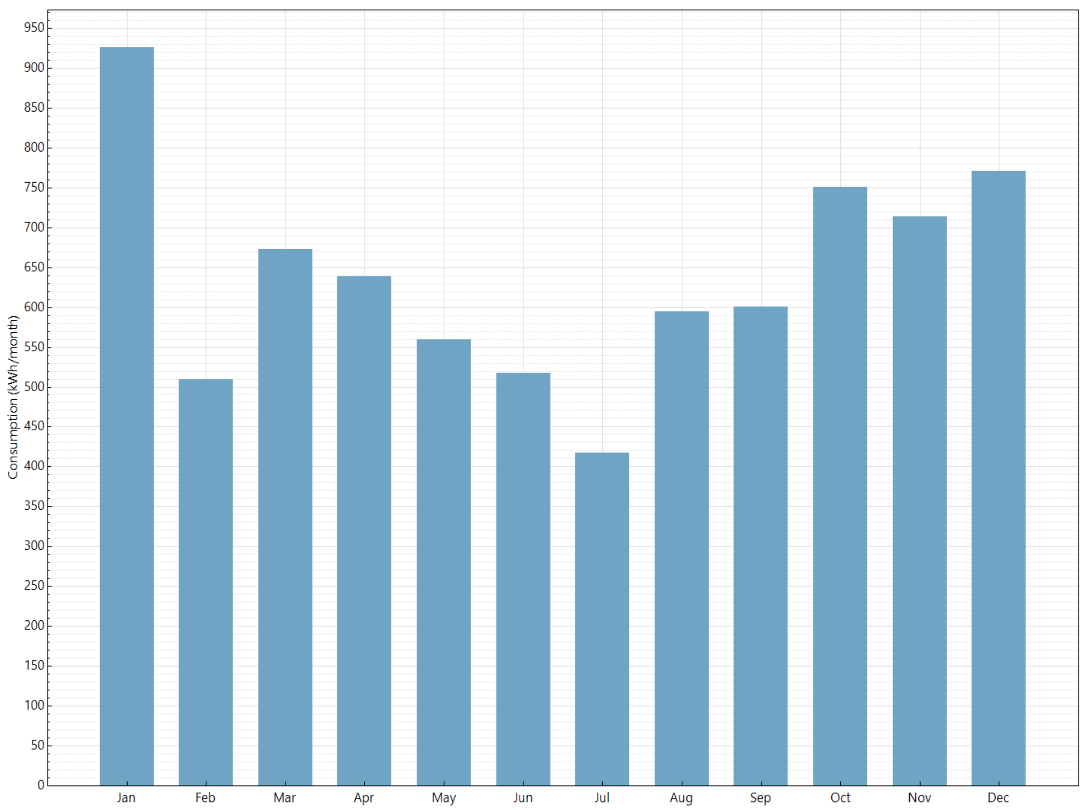

Figure 41. *Monthly consumption of semi-detached house with district heating (instead of electric heating).*

As can be expected, the monthly consumption is highest in winter and lowest in the summer, as it was for the first house. However, the power consumption in this house does not fluctuate as much as it did for the first house. For example, the difference between the electricity consumption in the second highest and the second lowest months is only 250 kWh, whereas the difference was almost 2000 kWh for the electrically-heated house. The consumption data in these simulations is much more stable, and also much lower than in the earlier simulations. For instance, the consumption in July is only 420 kWh, rather than the 900 kWh used in July in the house with electric heating.

Simulations with PV systems ranging from 1.5, 3.5, 7.0 to 10.7 kW were done with sonnenBatterie systems ranging from 4 kWh to 16 kWh of capacity. The optimal BES system is chosen for each of the PV systems, and a comparison is made with the earlier simulations. The profitability of each of these PV-BES systems is analyzed and compared with the earlier profitability calculations.

The first simulation was done with a 1.5 kW PV system, for which the smaller BES seems to be optimal. As such small PV systems generate so little excess electricity anyway, no BES system is really useful.

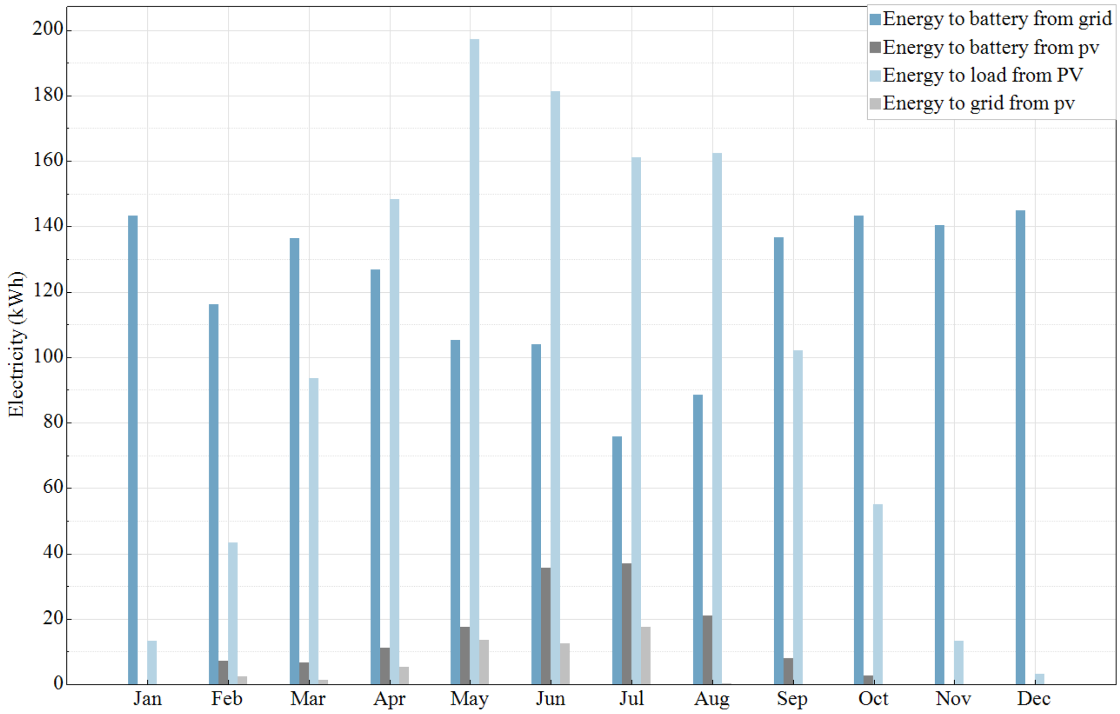

Figure 42. *1.5 kW PV + 4 kWh BES without electric heating.*

The simulations were then done with the 3.5 kW PV system. The earlier simulations had already indicated that a 4-8 kWh BES capacity would be optimal for this system, so the 8 kWh BES was chosen. The results are shown in Figure 43.

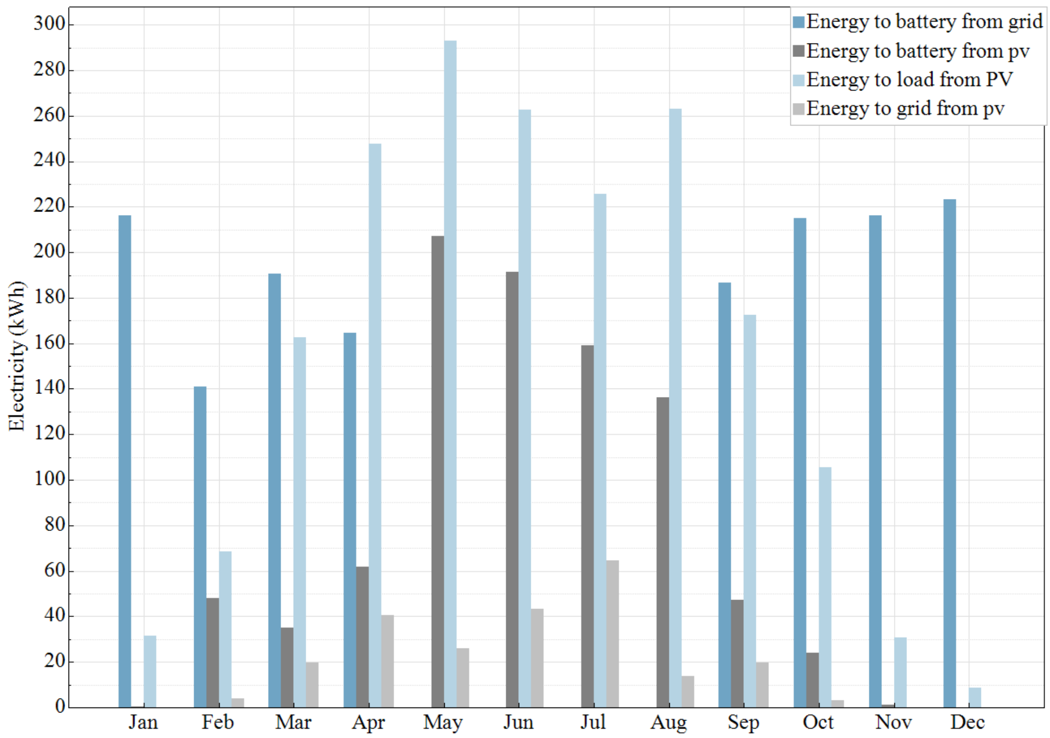

Figure 43. *3.5 kW PV + 8 kWh BES without electric heating.*

The graph shows that in July, when the total energy consumption of the house is lowest, excess PV production is sold to the grid at the rate of 65 kWh/month. A larger battery capacity would not reduce this by much.

With a 7 kW PV system, the differences between the heating methods start to become apparent. With a monthly consumption of only 400-600 kWh, the PV system produces excess electricity far beyond the storage capacity of even the highest BES. Even with the 16 kWh BES system, more of the PV production is sold to the grid than is charged to the batteries. Figure 44 shows the results of the simulation with this system.

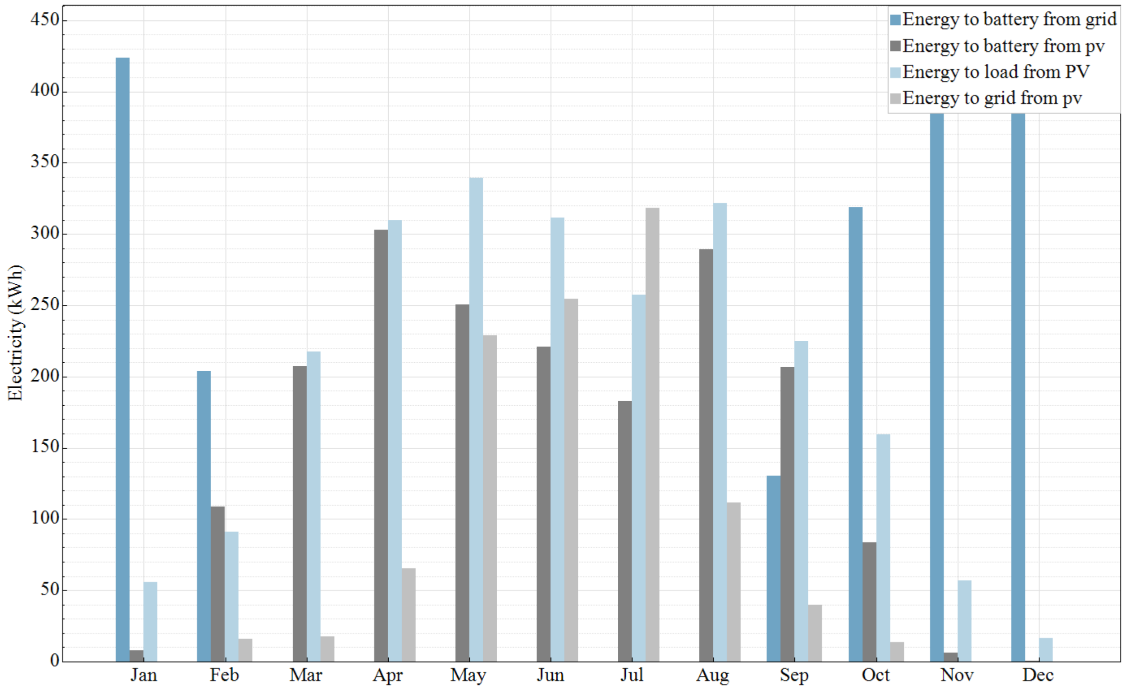

Figure 44. *7 kW PV + 16 kWh BES system.*

Even with higher consumption, a 10 kW PV system needs a 16 kWh BES system by its side. With the lower consumption data, it is clear that at least the 16 kWh BES system is needed for this size of PV system, as is shown in Figure 45.

Even with largest BES system, a great deal of the overproduction has to be sold to the grid. For a domestic residence, it is not wise to invest in a 10 kW PV system, even if the BES system is included in the deal. Even with a 7 kW PV system, the investment decision starts to be questionable. Once again, it has to be remembered that the sonnenBatterie has a maximum charging and discharging power of 3.3 kW, which also limits the effectiveness of the BES. This is why using a still larger capacity BES system would not make much difference.

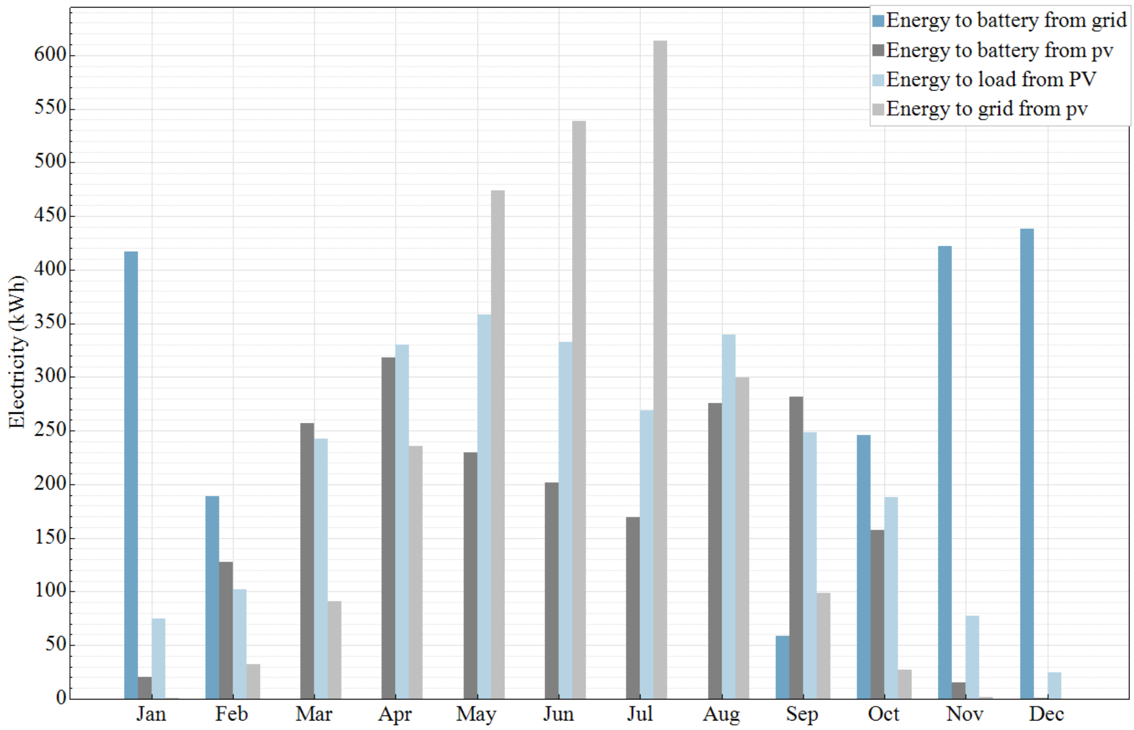

Figure 45. *10.7 kW PV + 16 kWh BES system*

The profitability of these systems is compared using yearly savings and the internal rate of interest. For the sake of comparison, the BES system chosen for the 7 kW PV simulations is the same as was used in the first set of simulations. Table 11 shows the results of the comparison.

Table 11. *Internal rate of interest and yearly savings of different PV+BES combinations with (data 1) and without electric heating (data 2).*

PV-BES system	Savings data 1 (€/a)	Savings data 2 (€/a)	Interest data 1 (%)	Interest data 2 (%)
1.5 kW, 4 kWh	17	22	-0.7	-1.2
3.5 kW, 8 kWh	65	79	1.7	0.8
7.0 kW, 12 kWh	136	130	2.4	2.4
10.7 kW, 16 kWh	213	159	2.2	0.4

As can be seen from the table, with the two smaller systems the yearly savings in the house with district heating are higher than they were with the electrically heated house. This could be explained by the fact that the TOU-shifting is more effective because the lower buy-prices for electricity had already been utilized in the house with electric heating. Also, with the smaller PV systems very little excess PV electricity need be sold to the grid. However, because the house has such low electricity consumption overall, with the larger PV systems most of the excess PV production has to be sold to the grid at a low price.

6.6 Lead acid battery vs Lithium ion battery

Here, the results of 3.5 kW PV and 8 kWh Li-ion system are compared to battery energy storage based on lead acid battery technology. The input data for this BES system, based on lead acid battery technology, is illustrated in Table 12.

Table 12. *Input data for lead acid battery simulation*

PV system	3.5 kW
Battery type	Pb-acid AGM
Battery capacity	8 kWh
Battery cost	175 €/kWh
Installation cost	1000 €/kWh
Lifetime	5 years

The other input data are the same as they were in the simulations made for the BES systems based on Li-ion technology. Installation costs are approximated by deducting the cost of the sonnenBatterie lithium batteries and then factoring in the cost of the lead acid batteries. In order to make the comparison relevant, the two systems must include the same functionalities and parts, so that the only differences arise from the use of the different battery technologies. The batteries need to be changed every 5 years, for which only the cost of the new battery is added. The escalation rate in the price of the lead-acid batteries is set at 1 %. The results of this comparison are shown in Table 13.

Table 13. *Comparison of 3.5 kW PV and 8 kWh BES with Pb-acid vs. Li-ion*

PV-BES system	Net present value (€)	Payback period (yr)	Internal rate of interest (%)
3.5 kW, 8 kWh Pb-acid	-4 216	+30	-0.9
3.5 kW, 8 kWh LiFePO	2 133	25.4	1.7

As can be seen from the table, it is clear that Pb-acid batteries cannot compete against LiFePo in this kind of solution. Lead-acid batteries have such a poor lifetime compared to the 10 000 cycles of the $LiFePo_4$ batteries that their 5-yearly replacement makes them prohibitively expensive. In addition, 8 kWh from a lead-acid battery is not truly comparable with the same capacity from a lithium iron phosphate battery because lead-acid batteries cannot be charged and discharged fully. In addition, the round-trip efficiency of the Pb-acid battery is so poor that it it is not economical to use it for TOU –shifting, although this is marginally beneficial with a li-ion battery.

Another problem with using Pb-acid batteries for this application is their size and weight. Aesthetically, a li-ion BES is much more appealing from a marketing point of view, as it is hard to sell a BES based on the old lead-acid technology. These systems will initially be mainly sold to the early adopters and technology enthusiasts. Such customers are more likely to be tempted by a li-ion-based BES system as it represents a new premium quality product, unlike a BES based on lead-acid batteries.

6.7 Economic forecast

This section analyses what the price of the BES system would need to be in order for a PV-BES system to be more profitable than only a PV system. In addition, the li-ion battery learning curve is used to estimate when this price range could be achieved. The simulations are only done for a 3.5 kW system, unlike the earlier simulations for the 4 differently-rated battery systems.

According to the simulations, a total installation price of 445 €/kWh (profitability line) would be needed for a BES-backed 3.5 kW PV system to be as profitable as a PV system without a BES. The profitability line is calculated with the same input data as the simulations in section 6.4 by iterating the total price of BES system and comparing the profitability of the PV-BES system to the profitability of PV system. This analysis will not consider the changing profitability of PV system or electricity prices of the installation day. The price of the systems is bound to decrease as the li-ion battery prices decrease. In addition, the price of the whole integrated system will almost certainly decrease. The decrease in the price of a 4 kWh BES is analyzed with four different annual price-decrease rates, as shown in Figure 46.

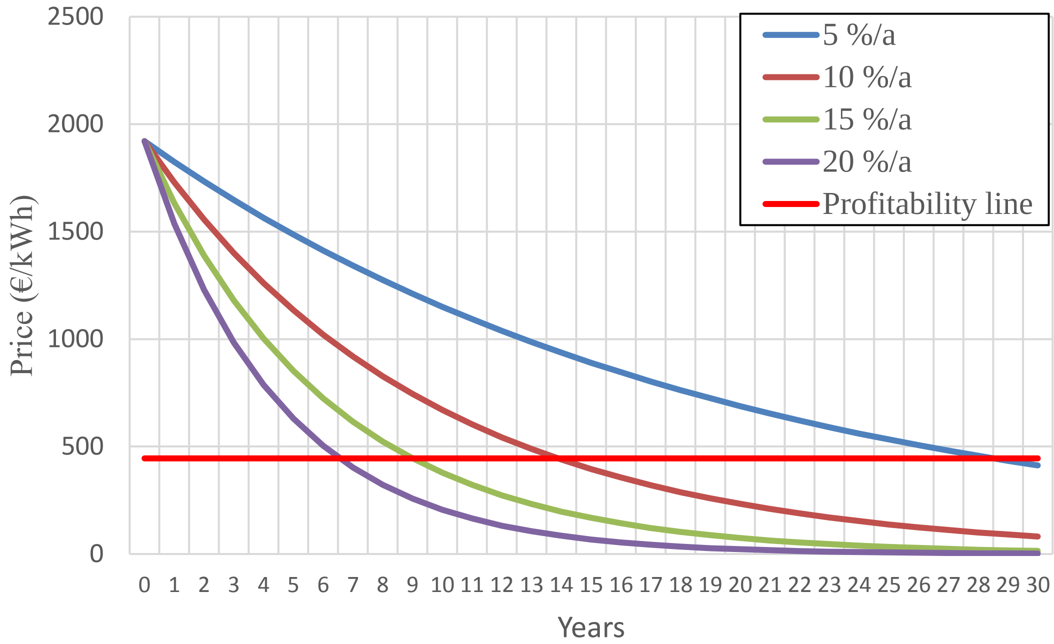

Figure 46. *Price decrease of 4 kWh BES system.*

With a 20 % p/a price decrease, installing the system could be profitable after 6.5 years, and with a 15 % p/a price decrease, this could take 9 years. With a 10 % p/a price decrease, it would take around 14 years, while at only 5 % p/a it would take 30 years before the system's price would be low enough to make it profitable for residential use. According to [30], the learning curve for li-ion batteries is 14-22 %, so the future looks hopeful.

6.8 Review of the results and sources of errors

With the electricity prices used in these simulations, it is clear that TOU-shifting is not very beneficial. The price difference is so marginal that the monetary benefits are almost consumed by the losses of the system. If the customer could use an electricity tariff based on the market price, and he could control the BES system optimally, then according to [53] Finland has the greatest potential of all the Nordic countries to benefit from TOU-shifting in a day-ahead market. However, the sonnenBatterie eco 8.0, for example, is not yet capable of optimizing TOU-shifting at spot market prices.

Many of the simulations were done with only one electricity load. The first house was heated with electric heating and its electricity consumption was around 24 MWh/a. If the load patterns of another customer were radically different, these results could be a little off the mark. The load profile in the summertime is more meaningful for PV use, and the heating method can also affect the profitability of TOU-shifting. If the base load in the summertime is lower than the loads used in these simulations, slightly larger BES systems should compensate for this, whereas if the summertime base load were higher, then smaller BES systems could be installed.

The effects of different heating methods were briefly analyzed with simulations in section 6.5. This analysis showed that using electric water heating in the nighttime decreases the potential profitability of the BES system through TOU-shifting. The consumption data used in 6.5 has a significantly lower daily consumption in the summer time than the data used in the earlier simulations. This means that more excess energy is produced from the PV system, so the BES system needs to have a higher capacity to compensate for this.

Although the simulations cannot exactly capture the actual operation of a BES system, some tentative conclusions can be drawn from the results of the study. The simulations were based on hourly data, so using shorter data intervals might affect the quality of the results. If the electricity price difference between night and day were greater, a BES system could be more profitable for TOU-shifting. The difference between the electricity prices used in the simulations was around 17 %, which meant that most of the monetary benefits come from storing the PV excess energy in the BES for later use. That is why recommendations for the size of a BES are only made in relation to the size of the PV system. Table 14 shows the recommended BES system sizes in relation to the PV system size for Finland.

Table 14. *Recommended BES system sizes in relation to PV system size*

PV system (kW)	<3	3	5	7	10
BES system (kWh)	4	4-8	6-12	10-16	16

With small PV systems (<3) battery energy storage is not essential, because so little excess PV energy is sold to the grid anyway. From 3 kW upwards, the BES systems start to be more beneficial.

The sonnenBatterie's maximum charging and discharging power of 3.3 kW is a limiting factor, as with bigger PV systems some of the excess energy has to be sold to the grid in the summer. Of course, any recommendations are subject to a number of variables such as consumption patterns and heating method. The best practice would be to size every system individually, although this may not always be a practical solution.

Unless the price of BES systems decreases dramatically, they are not going to be profitable for the residential customer for quite some time yet. Based on the prices used in the simulations, TOU–shifting only contributes 20 % of the total benefits for a BES, while 80 % comes from storing the excess PV energy.

7. CONCLUSIONS

This thesis analysed the profitability of using a battery energy storage (BES) system in parallel with photovoltaic (PV) system in Finnish residential applications. One of the main goals of the thesis was to compare feasible battery technologies and choose an appropriate product for Naps Solar System's new BES offerings. The techno-economic comparison of the main battery types showed that the best cell chemistry for this application was the lithium iron phosphate battery. The chosen cell chemistry is the safest of the lithium-ion chemistries, and it has the longest cycle lifetime, making it more appealing and more cost-efficient in the long run than any other cell chemistry. Therefore, the lithium iron phosphate ($LiFePO_4$) cell chemistry was chosen, and the most suitable product on the market was found to be the sonnenBatterie eco 8.0. The BES can be sized according to consumption and production data. The capacity range is from 4 kWh to 16 kWh and the nominal power is 2.5-3.3 kW. Simulations were made using the technical details of the chosen system.

The thesis presented an overview of the theory behind photovoltaic modules, and the effects of different operating conditions and inclinations for the PV modules. It also presented an overview of the current situation in the solar industry, both globally and in Finland. It is clear that the operating conditions have a huge impact on the operation of a solar cell. Although Finland has almost the same annual solar energy yield as in Germany, in Finland most of the solar energy is gathered in the summertime, when the electricity demand in residential houses is at its lowest, and vice versa in the winter. In addition, in Finland there are no net tariffs, or any other incentives to persuade a potential customer to switch to solar power. Excess PV production has to be sold to the grid at a low price, so there is little profit to be had in excess capacity in the PV systems. However, there are other considerations, and a BES system can be used in parallel with a larger PV system in order to make the customer more energy-independent.

Three different battery technologies were compared in detail, namely lead acid, nickel and lithium ion. However, the thesis also presented an overview of other energy storage technologies. Flow batteries may become one possible solution for residential applications in the future, and the possibility of using hydrogen fuel cells for seasonal storage was also discussed.

The basic operation of grid-connected battery energy storage systems was analyzed and two possible topologies were introduced. Topology (a) used a so-called hybrid inverter in addition to two DC/DC converters, while topology (b) had two inverters, for both the PV and the battery. Although topology (a) is cheaper, and could therefore be used for installing completely new PV-BES systems, topology (b) is more easily installed in parallel with an existing PV system, which made it more suitable for this application.

The thesis also analysed the cost benefits and safety aspects of battery energy storage. There are two main monetary benefits. The first, and by far the largest cost savings, come from storing excess PV electricity production in the batteries and then using that energy when the PV cannot produce enough energy for the customer's needs. The other monetary benefit comes from so-called time-of-use –shifting, where the BES system charges from the grid at night when the price of electricity is lowest, and uses that energy at other times in the day when the residential customer needs it most.

The safety of a BES system in residential applications is extremely important. There are always some risks when packing lots of energy into a small space, but people can still use it safely as long as they observe a few basic safety procedures. For example, it is of the utmost importance that lithium-ion batteries are handled and transported carefully. However, cell and battery manufacturers can also affect the safety of the system by using different cell chemistries. Of the many different lithium-ion cell chemistries available, the lithium iron phosphate battery is clearly the safest. Not only is its thermal runaway point the highest, its energy release in thermal runaway is much lower than with other cell chemistries. Lithium-ion batteries are usually equipped with integrated electronic circuitry to prevent overcharging or undercharging. Such circuitry can also have a significant effect on the safety of the system, so the manufacturer of the battery module must be reliable.

There are a number of factors which affect the profitability of the battery energy storage system. Because a PV- BES system is mainly used to avoid buying electricity from the grid, the market price of electricity has a significant impact on the overall profitability of the system. Finland and other Nordic countries have slightly cheaper electricity than in central Europe, which actually makes these systems appear less profitable here. However, if the customer has a higher than average electricity consumption, and can make optimal use of time-of-use-shifting, a PV-BES may be slightly more profitable. If the customer could use the spot prices for electricity, a BES could be still more beneficial. Another factor could be that if the government would introduce more incentives for domestic consumers to switch to solar power, or if the energy companies were to introduce new ways of pricing the electricity, the profitability of PV and BES systems could be better. The level of inflation and the price escalation of electricity also has significant impact on the profitability of these systems. Any of these variables could change dramatically in the system's lifetime, so the profitability of these systems is difficult to calculate accurately. Nevertheless, by making some educated assumptions about these values, it is possible to calculate the possible profitability of these systems. The calculation methods used include the net present value, payback period and internal rate-of-interest methods.

The technical data of the chosen battery energy storage system (sonnenBatterie eco 8.0) was used to simulate the operation and calculate the profitability of these systems. As a result of these simulations, it is clear that BES systems are not yet a very profitable investment. However, an optimally-sized PV+BES system should reach its payback point within the 30-year analysis period, so it would have a positive net present value. The internal rate of interest is somewhere between 1-3 %.

Storing the excess PV electricity production in batteries and using that energy instead of buying from the grid has the biggest impact on the overall profitability of a BES system. It is shown here that the most profitable way of using a BES is to take advantage of TOU-shifting in winter (starting from September at the earliest, and ending in April at the latest) and to use all the available BES capacity to store excess PV electricity in the summertime. With small PV systems, it could be more beneficial to use the system for TOU-shifting throughout the year, because there is so little excess energy to store. With bigger PV systems, TOU shifting accounts for approximately 20 % of the annual savings while 80 % comes from storing the excess PV production to be used later.

The thesis concluded with some general recommendations based on the size of the PV system. Based on the simulations (with both sets of consumption data) it was shown that a BES system is not very useful with small PV systems ranging from 1 kW_p to 2 kW_p. With 3 kW PV system, the recommended BES system is the smallest one, with a capacity of 4 kWh. With a 5 kW PV system, the recommended BES sizes are from 6-12 kWh. With the larger PV systems, ranging from 7-10 kW, even the biggest system of 16 kWh can be beneficial.

All in all, at the moment a BES cannot be sold to residential customers on the basis of its profitability. Early adopters and technology enthusiasts might invest in a BES regardless of its price or profitability. If the BES system could act as a source of back-up power in outages, it could become more popular in rural areas of Finland. A BES system can also be thought of as more than just an energy storage system. It is also the first step towards developing one’s house into a Smart Home, which would be suitable for integration into the Smart Grid of the future.

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