MSc Program
Renewable Energy in Central and Eastern Europe

Photovoltaic (PV)-Battery Systems:
How does the behaviour of users in a typical Austrian household influence the performance of a PV fed home-battery system?

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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24 April 2017

Affidavit

I, **PAUL CHALOUPKA**, hereby declare

1. that I am the sole author of the present Master Thesis, "*Photovoltaic (PV)-Battery Systems: How does the behaviour of users in a typical Austrian household influence the performance of a PV fed home-battery system?*", 72 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

Vienna, Wednesday, 24 April 2017 ________________________

Date Signature

Abstract

At the moment, a variety of battery technologies and systems are available in the market. And even more technologies and systems are in research. Moreover, there are wide areas of application for the use of batteries, which again impose very different (technological) requirements on each battery technology or system. Therefore, a concise statement of a single best technology for the future market cannot be easily given.

According to the study of the “Energietechnischen Gesellschaft im VDE” batteries will additionally lift the interest in photovoltaics (PV) in the residential field (Aundrup, et al., 2015). As a matter of fact, declining module and balance of system (BOS) costs of PV, decreasing PV “Feed-in Tariffs” (FiT) as well as rising electricity prices for the end costumer enable for PV Battery Energy Storage Systems (PV-BESS) favorable market conditions. Homeowners, who produce, store and use their local generated energy, will not just become prosumers, but also derive an additional benefit of being more independent from any future energy price fluctuations, shifts of the market or general market failures.

As area of application residential households in Austria have been chosen. In a first step this master thesis briefly analyses the available technologies and basic functionality of residential PV systems. More time will be spent to review and analyze the past and future market of available battery technologies and systems in a technological and economical perspective with respect to the already stated form of application. The most appropriate PV and battery technology out of this analysis will be chosen and used in the household as underlying PV-BESS. It follows from the text above, that in a case of individual households the behaviour of the persons living in that household might have a significant influence on the overall performance and durability of the battery system. But which behaviours cause what effects and to which extent?

In this master thesis, the dataset of the “Multifunktionales Batteriespeichersystem” (MBS) from R. Sterrer and W. Prüggler has been used. In a project consortium[1], they compiled load profiles for four different Austrian households. Each household and person of the four homes has been outfitted with its own pattern of behaviour. Together with the chosen PV-BESS this paper will identify similarities, contrasts and other tendencies of behaviours, which might be significant in influencing performance and durability of the whole system. Additionally, a favorable outcome of this master thesis would be a classification of PV-BESS type and size for each of the observed households.

All the calculation will be done in Excel and further use of sensitivity analyses will show the dependencies of each PV-BESS. It will be necessary to define general assumptions, but those will be elaborated in more detail later in the thesis. By having different sources with uncertainty in its inputs, the uncertainty of the output of the PV-BESS in the specified application can be better understood.

As a consequence, this master thesis will try to answer the following research question:

Photovoltaic (PV)-Battery Systems: How does the behaviour of users in a typical Austrian household influence the performance of a PV fed home-battery system?

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[1] Project consortium was composed of FH Technikum Wien – Institut für Erneuerbare Energie, EVN AG, ATB- Becker, KEBA AG, Cellstrom GmbH und der TU WIEN – Energy Economics Group.

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List of Abbreviations

µ-Si	Micromorphous Silicon
a-Si	Amorphous Silicon
AHI	Aqueous Hybrid-Ion
BoS	Balance of System
BESS	Battery Energy Storage System
BMS	Battery Management System
CAGR	Compound Annual Growth Rate
CCT	Clean Coal Technology
CdTe	Cadmium-Telluride
CI(G)S	Copper-Indium-(Gallium)-(Di-)Selenid
CPV	Concentrated Photovoltaics
CZTS	Copper-Zinc-Tin-Sulphur-Selenium
DINCI HH	Double Income no Kids' Household
DMD	Direct matched Demand
DSM	Demand Supply Management
EEG	Erneuerbaren-Energien-Gesetz
EMS	Energy Management System
EPIA	European Photovoltaic Industry Association
EPC	Engineering, Procurement and Construction
FNSKPL	Family with two Non-School Kids, one Parent in Parental Leave
FSKNPL	Family with two School-Age Kids, no Parental Leave
GWp	Gigawattpeak
HH	Household
kV	Kilovolt
kWh	Kilowatthours
kWp	Kilowattpeak
Li-ion	Lithium-Ion
MBS	Multifunktionales Batteriespeichersystem
mc-Si	Mono-Crystalline Silicon
MMPV	Monograin Membrane Photovoltaik

MWp	Megawattpeak
P HH	Pensioners' Household
Pb-acid	Lead-Acid
PPA	Power Purchase Agreement
PV	Photovoltaik
PV-BESS	Photovoltaic – Battery Energy Storage System
R&D	Research & Development
sc-Si	Mono-Crystalline Silicon
TRL	Technology Readiness Level
VRFB	Vanadium Redox Flow Battery

Chapter 1: Introduction

The introduction of incentive systems for PV in various countries supported the growth in the last decade (see Figure 1). As a consequence, a greater number of players became active in the market. Higher production values, more and bigger PV projects – together with economy of scale – led to decreasing costs of PV (see Figure 4). Which again, forced politics to lower incentives for PV over the years. At a certain point in time, solely incentives were not attractive for the construction of a residential PV plant anymore. But as soon as the price of produced kWh (of the residential PV plant) was less than the costs of kWh for the end consumer (including grid fees, taxes, etc.) the feasibility of the residential and commercial PV plant changed. Whereas in the first case, always the maximum size of the roof top has been used in order to receive maximum incentives. In the latter case, the self-consumption of the system gain additional importance for the investor. Henceforth, the size of a modern residential PV plant is depending on the total energy demand of the household itself and not just on the incentive system in place in a certain country.

The urge to a higher degree of self-consumption positively influenced the usage of storage systems in this segment (see Figure 8). Due to the higher demand of battery systems in various segments (e-mobility, e-bikes, portable PC's, power tools, household devices, etc.) the costs of production, assembling, etc. decreased, while standardization in configuration and installation increased (see paragraph 2.3.). The implementation of additional incentives for batteries supported this development. In Germany, such a system has been successfully implemented already in 2013, in Austria in 2014. According to the yearly report from the higher technical school in Aachen from 2016, almost every second home PV installation has been equipped with a battery system in Germany in 2015. Additionally, investments in R&D and production lines/processes of mutli-billion dollar companies like Tesla or Daimler support this trend (Badeda, et al., 2016). More details about the market development can be found in chapter 2.

Chapter 2: Technical Overview and Market Analysis

2.1 PV Systems – Technology and Market Analysis

The rise of PV began in Germany in 2000, because of the introduction of the "Erneuerbare-Energien-Gesetz", EEG (Renewable Energies Act, REA). The German government launched in this law also a so-called program of "Feed-in Tariffs" (FiT), which obliged energy providing companies to buy decentralized produced PV energy (from ground-mounted as well as residential and commercial PV plants) over a certain time (e.g. 20 years) to a "higher-than-market" price from the producer. The upcoming investment opportunities were financially feasible and – due to the governmental coverage – obtained a calculable risk. Additional regulations like the rule of strict priority for renewable energy over "normal" fossil or nuclear energy on the German market supported this trend and minimized the risk further. Despite many complaints (because of high costs for the government and therefore a later introduction of a "Ökostromabgabe", an extra green energy tax) and changes of the law over the years, the program supported the introduction and development of photovoltaics in general. Similar programs have been introduced by more than 47 governments all around the world (Brake, 2010).

The first years of this ongoing growth of actual PV installations has almost exclusively been taken place in European countries, whereas more recent installations are mostly constructed outside of Europe, like the US or China as main driver of growth in the sector. Figure 1 shows a continuous increase in PV installations from 2005 to 2016 and even an expected scenario till 2020 (Hill, 2016). European climate strategies and targets like 2020 climate & energy package, 2030 climate & energy framework and 2050 low-carbon economy as well as the global climate deal support this trend and show the recent awareness and general significance of the topic.

Source: GTM Research *Global Solar Demand Monitor Q2 2016*

Figure 1[2]: Global PV Demand 2005 - 2020E (Hill, 2016)

According to the numbers of GTM Research, an additional 55GWp has been added alone in 2015 to a total of 252GWp PV installations worldwide. The figures also show some of the local political decision making, like FiT pullbacks in China/U.K. or FiT extensions and new tenders in U.S. and India, which are still influencing the final construction of PV plants in a country strongly (Hill, 2016). Nevertheless, the industry is getting closer to grid parity[3] every year. Recent announcements show that the price per kWh at big scale ground-mounted PV plants can be even below the market price of traditional energy carrier like fossil fuels. At the moment, India has installed around 4.4GWp of installed utility solar capacity and has another 16GWp of tenders allocated or in process, which are expected to be operational by 2017. The latest tender of solar energy capacity in India has achieved a low price of 0.0593€/kWp[4] for a 70MWp PV plant, which is lower than the current price of coal-powered energy generation in India

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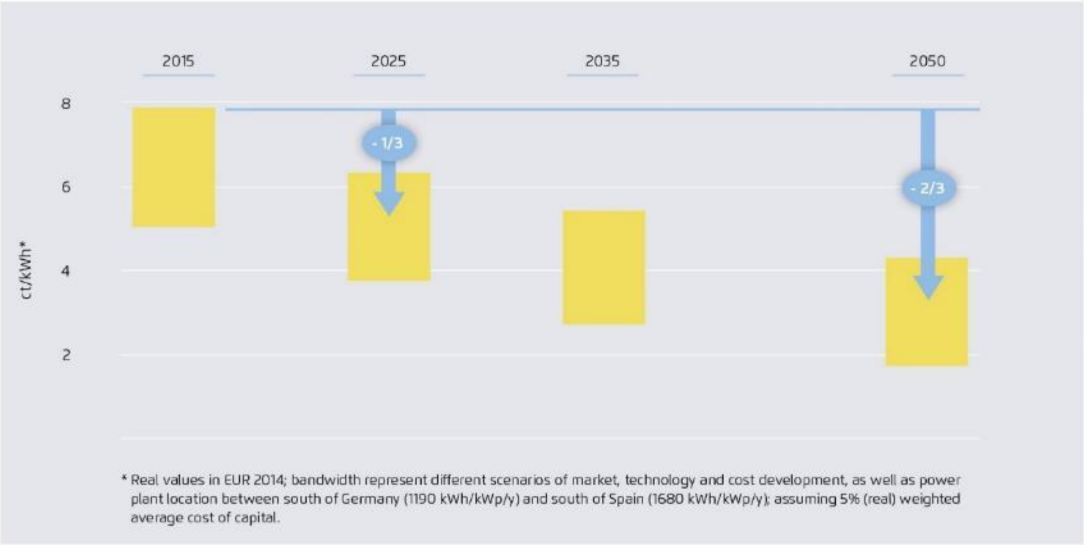
[2] Compund Annual Growth Rate (CAGR): "the mean annual growth rate of an investment over a specified period of time longer than one year" (Wayman, 1999)

[3] It is important to add, that there are various calculations of the expression "grid parity" in the literature, because it strongly depends from which point of view (utility, consumer, etc.) and which variables (just peak prices, incentives, external costs, etc.) are considerend in the calculation.

[4] 4.34rupees/kWh; calculated with the daily exchange rate, acquired from http://www.xe.com/currencyconverter on the 05. December 2016

(Parkinson, 2016). Prices like these are not just possible in India, Mexico or China. A utility in Nevada has just recently agreed in a PPA[5] upon a purchasing price for solar energy from Playa Solar 2, a 100MWp Frist Solar PV plant, of 0.0359€/kWh[6] (Clover, 2015). Even if the actual purchasing price of this PPA is in the end 0.0613€/kWh[7], due to a 3% escalation clause and a 30% Investment Tax Credit, the numbers show the overall potential of the photovoltaic technology. The respected German research institute Fraunhofer Institute for Solar Energy Systems recently published in the study "Current and Future Costs of Photovoltaics" as main conclusions the following: *"In a few years, solar energy plants will deliver the most inexpensive power available in many parts of the world. By 2025, the cost of producing power in central and southern Europe will have declined to between 4 and 6 cents per kilowatt hour, and by 2050 to as low as 2 to 4 cents."* (Fraunhofer ISE, 2015).



* Real values in EUR 2014; bandwidth represent different scenarios of market, technology and cost development, as well as power plant location between south of Germany (1190 kWh/kWp/y) and south of Spain (1680 kWh/kWp/y); assuming 5% (real) weighted average cost of capital.

Figure 2: Cost of Electricity[8] from New Solar Plants in Southern and Central Europe (Fraunhofer ISE, 2015)

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[5] PPA "Power Purchase Agreement": commercial term for a contract between two parties, one which generates electricity and one which is looking to purchase it

[6] 0.0387$/kWh; calculated with the daily exchange rate, acquired from http://www.xe.com/currencyconverter on the 05. December 2016

[7] 0.066$/kWh; calculated with the daily exchange rate, acquired from http://www.xe.com/currencyconverter on the 05. December 2016

[8] Weighted Average Cost of Capital (WACC): "the average interest rate a company must pay to finance its assets. As such, it is also the minimum average rate of return it must earn on its current assets to satisfy its shareholders or owners, its investors, and its creditors" (Peavler, 2016)

A similar picture can be seen with the price learning curve for c-Si and thin-film (see Figure 3) (ISE, 2016).

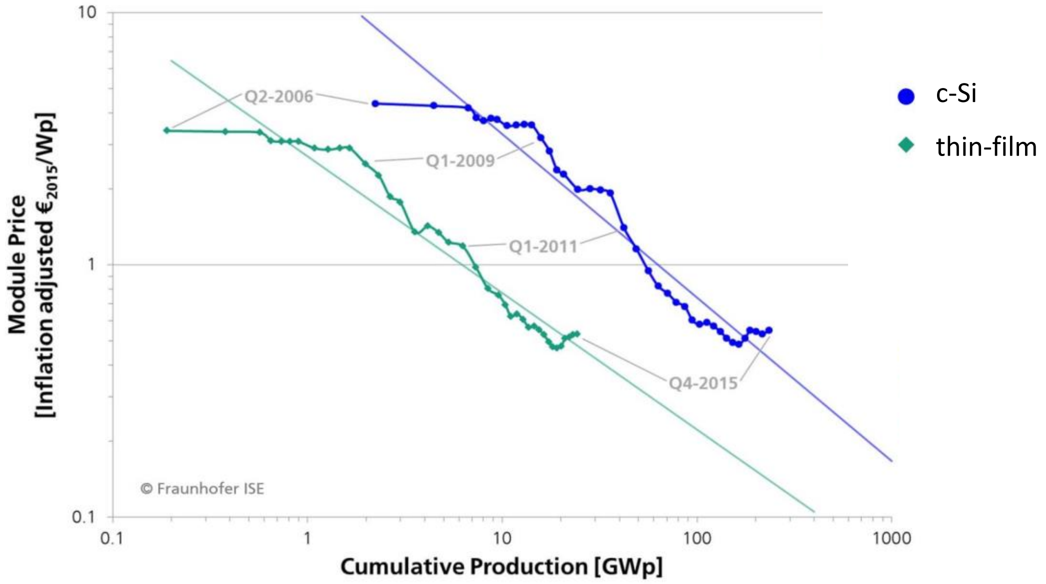

Figure 3: Price Learning Curve by Technology (ISE, 2016)

But how are such reductions per kWh possible? Various factors (services and components) along the supply chain influence the final costs of a PV installation. The International Renewable Energy Agency (IRENA) conducted a study this year about the solar cost reduction potential till 2025[9]. In Figure 4 the most important segments of a PV installation have been elaborated and weight with its actual cost impact in each year between 2009 to 2025E (IRENA, 2016).

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[9] Please notice, that all upcoming Figures from the IRENA study are in U.S.§; actual convertion rate EUR/USD: 1.0655 acquired from http://www.xe.com/currencyconverter on the 05. December 2016

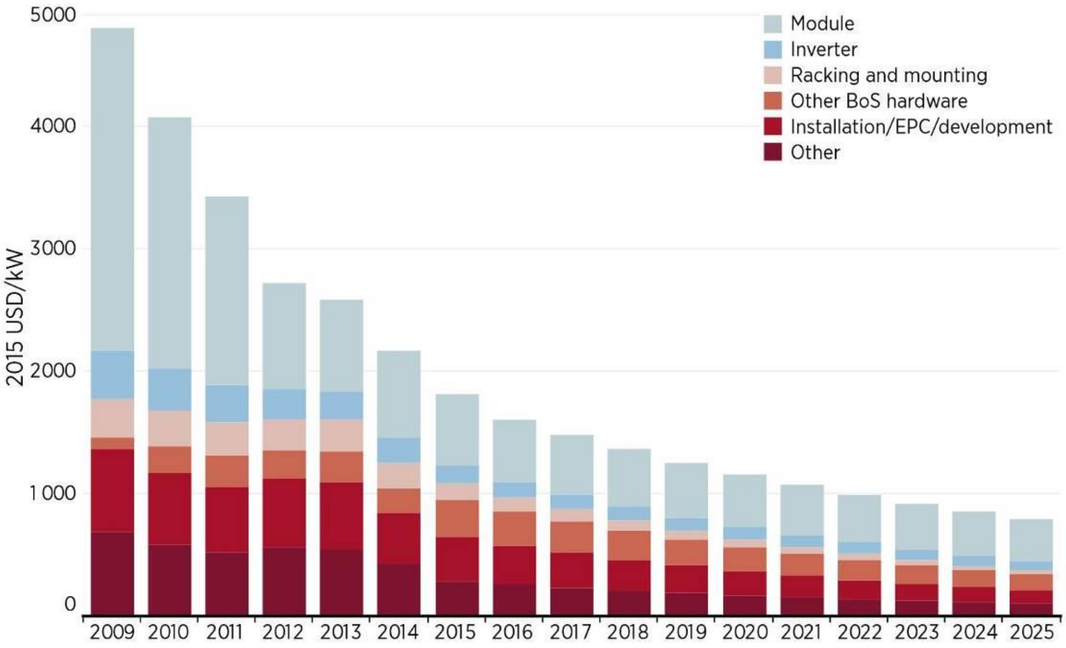

Figure 4: Global Weighted Average Utility-Scale Solar PV Total Installed Costs in U.S.$ (2009-2025E)[10] (IRENA, 2016)

The cuts in each of the segments are mainly driven by technological improvements in solar PV modules, manufacturing advances, competitive pressures, economies of scale and reductions in BoS (red segments in Figure 4). With learning curves between 18 and 22%, historically the main driver for the reduction in costs was the continuous and steady decline in module costs (contributed around 68% just between 2009 and 2015). It is expected that this development is going to change and the largest reduction carrier of costs might be dedicated to the BoS until 2025, using 2015 as cost reference level. Latter might be responsible for up to 70% of the cost reduction in 2025, reflecting the high average level of BoS costs today relative to best practice. Whereas the inverter technology is predicted to have overall the smallest impact in cost cutting in the future (IRENA, 2016).

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[10] BoS „Balance of System“: includes all remaining components of a PV installation other than the main equipment, like DC components, wiring, switches, etc. (also see Table 1); EPC “Engineering, Procurement and Construction”: contracting arrangement, where the Contractor is responsible for all activities (like planning, design, engineering, procurement, construction, etc. till the handover of the final project to the Client

So far, this chapter has given an overview of the market development worldwide as well as predictions for possible future scenarios. Furthermore, various important cost drivers of the photovoltaic have been identified. Depending on the region and country the cost drivers vary in size, which again leads to various costs of electricity for PV around the world. After this short global market and cost analysis, for answering the research question, it is also necessary to analyse the current situation of Austria in more detail. How is the market situation currently in Austria?

2.2 PV Systems – Austria

Before the introduction of the “Ökostromgesetz” in Austria in 2002, there were solely a few pioneers and innovators who actually installed a PV system on the roof top in Austria. After this law, a minor increase of installations was noticeable per year. But it took some more years before the “Klima und Energiefond” adapted this law and implemented an incentive system for PV in Austria in 2009. This was the turning point in the Austrian PV market and from this date on significant numbers of PV were added year by year (see Figure 5) (Biermayr, et al., 2016). In 2013, the money at disposal in the incentive system has been extended, which led to a surge in PV installation. Without this additional incentive, the annual rate of increase seems to stagnate at around 160MWp per year, even slightly decreasing (Fechner, et al., 2016).

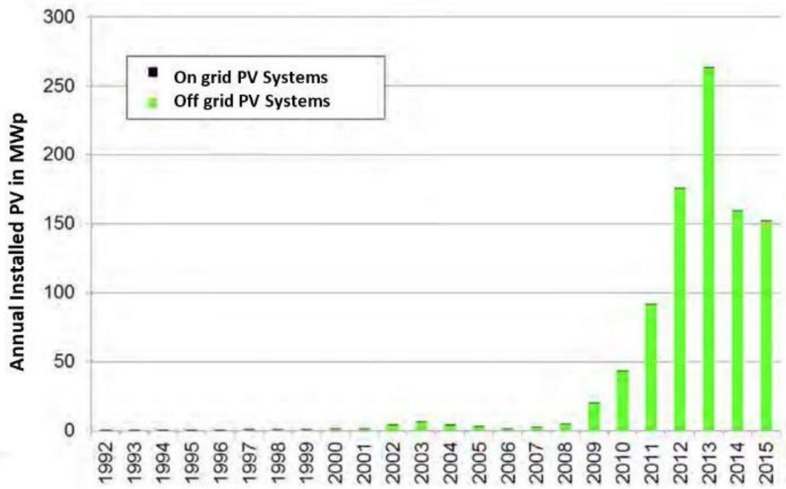

Figure 5: Annual Installed PV in Austria in MWp (Biermayr, et al., 2016)

Altogether the amount of installed PV reached 1GWp in Austria in 2016, which accounts for about 2% of the Austrian demand for electricity (to end consumer). Figure 6 illustrates the mean price of a 5kWp PV system in Austria from 2011 to 2015. In the last 7 years, the total installation costs dropped by about two-thirds (-68%) (Fechner, et al., 2016). The stated minimum was even at €1,350/kWp for a 5kWp system in 2015. Furthermore, the stated mean price of a 10kWp system in Austria in 2015 was at €1,274/kWp, with the minimum at €1,000/kWp (Biermayr, et al., 2016). This price-, respectively cost- structure comes very close to the German PV sector, which is one of the cheapest markets for PV, due to its maturity and high competition (IRENA, 2016). As a consequence, the electricity production costs of PV systems lie in between 7.9-9.8 €cents/kWh compared to natural gas, which lies between 7.5-9.8€cents/kWh in Austria (Fechner, et al., 2016) (compare to costs of Southern and Central Europe in Figure 2).

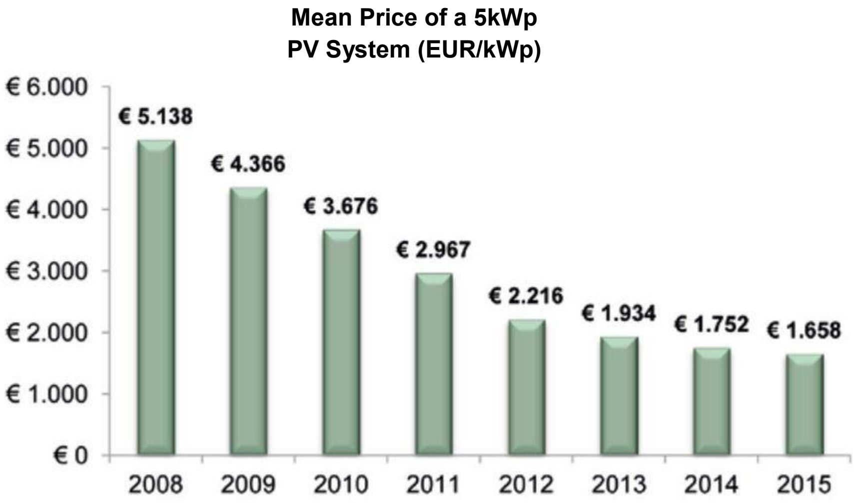

Figure 6: Mean Price (EUR/kWp) of PV Total Installed Costs in Austria (Fechner, et al., 2016)

If the current situation remains with growth rates of about 150MWp per year, Austria is most probably not going to reach any international agreed concessions, like from the "International Panel of Climate Change" (IPCC), which calls for a reduction of CO2 emissions of -50 to -85% until 2050. European climate strategies and targets like 2020 climate & energy package, 2030 climate & energy framework and 2050 low-carbon economy as well as the global climate deal won’t be reached without a major increase in effort as well as investments in Austria (Fechner, et al., 2016).

85% of all installed PV systems in Austria in 2014 were rooftop mounted installations. So, the greatest part of all PV installation is mounted on rooftops in Austria. It is estimated, that the full potential of suitable areas on rooftops and facades in Austria is about 230km^2 (170km^2 area on rooftop and 60km^2 on facades). The “Technologie-Roadmap” from Hubert Fechner, et al. from 2016 demonstrates that this rooftop potential would be enough to reach 100% renewable energy in Austria by 2050[11]. Higher module efficiencies, broader fields of applications, like on noise barriers, traffic areas, dumpsites, etc., have not been included in this calculation of a future scenario in 2050 (Fechner, et al., 2016).

To sum it up, in the last 7 years the installation costs of a PV system decreased by 68% in Austria. The production cost of electricity for PV is already almost as low as for natural gas. So, the question remains, why is the annual rate of increase so little in Austria? The solution might be a mishmash of adaptations, changes, innovations and many more things. Politicians, scientists, jurists, ecologists, scholars, engineers, architect, investors, homeowner; all have to do their part in order to achieve 100% renewable energies in Austria in 2050. But an appropriate incentive system in place without much red tape is, and will be, the most efficient tool in order to increase the amount of PV substantially (Fechner, et al., 2016).

According to the study of the “Energietechnischen Gesellschaft im VDE”, one way to additionally support (residential or commercial) rooftop mounted PV will be the integration of an affordable and intelligent home battery into a PV Battery Energy Storage System (PV-BESS) (Aundrup, et al., 2015). In addition, declining module and BoS costs of PV, decreasing FiTs as well as rising electricity prices for the end costumer enable favorable market conditions for PV-BESS. Homeowners as well as proprietors of firms, who produce, store and use their local generated energy, will not just become prosumers, but also derive an additional benefit of being more

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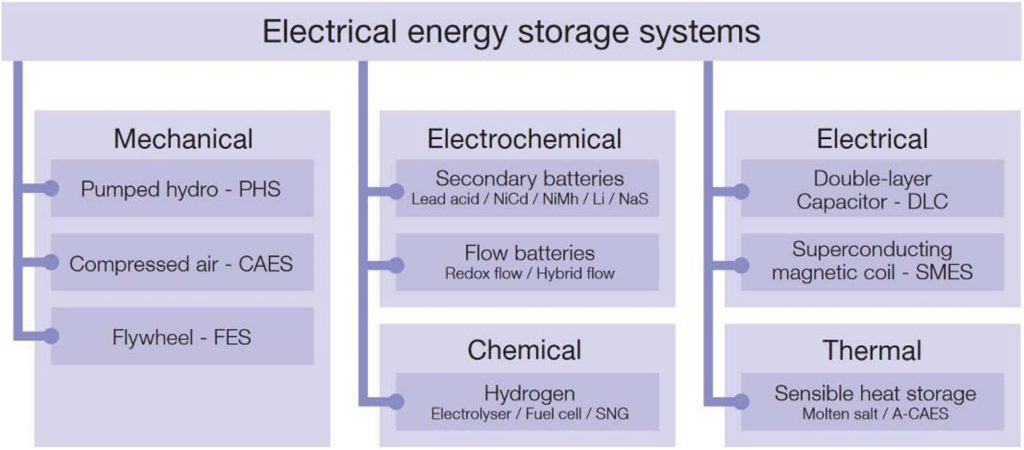
[11] For further information about the concept, calculations and implementation of this “Technologie-Roadmap” from Hubert Fechner, et al., please visit http://www.pvaustria.at/wp-content/uploads/1615_technologie_roadmap_photovoltaik.pdf

independent from any future energy price fluctuations, shifts of the market or general market failures. Therefore, it is necessary to devote the next chapter of this master thesis to a deeper analysis of storage and battery systems.

2.3 Storage Systems – Technologies and Market Analysis

An electrochemical battery is just one of many possible energy storage systems (ESS). One of the most common – and biggest in amount – forms of energy storage today is pumped hydro, which counts for 97% of the existing energy storage capacity (European Commission, 2017). Water is pumped up the hill into a water reservoir at times of low energy prices, and released again downhill through hydroelectric generators at times of high energy demand (peak prices). This old form of energy storage is clean, efficient, reasonable and scalable, but the downside is that in many regions around the world it is not a possibility, because of the absence of enough water or mountains/higher regions. This type of ESS is categorised as mechanical energy storage, using gravity as natural force to generate electricity. There are also other energy storage systems, like electrochemical (also BESS), chemical, electrical and thermal energy storage, each having again subcategories in order to fulfill certain tasks (IEC, 2011).

Table 1: Types of Energy Storage (IEC, 2011)



The field of application of storage systems ranges from smoothening of short-term load fluctuations in seconds to seasonal balancing of the energy fluxes during the seasons of the year. Therefore, the technical requirements of an ESS are diverse, regarding the energy and power density, efficiency, reaction time, cycle stability and other key figures. Various storage technologies are already in use for many years in the market, like lead-acid- (Pb-Acid), nickel-metal hybride- (NiMH), redox-flow- and lithium-ion-4V (Li-Ion, 4V) batteries as well as pumped hydro and flywheel energy storage (as short-term storage). Whereas others are in development, like specific electrochemical storage systems as hydrogen and fuel cells, pumped hydro with low height of fall, hydraulic storage or post lithium-ion-5V (Li-Ion, 5V). Latter is to be expected on the market with much higher energy density in about 5 years (Klima- und Energiefonds, 2016).

The two types, which are mostly used in PV-BESS are Pb-acid and Li-ion batteries (see Figure 9) (Badeda, et al., 2016). So, the next chapter will shortly describe both technologies and highlight current key figures including a short glimpse in the future (ISEA, 2016).

2.3.1 Lead-acid- (Pb-acid) batteries

This battery technology is already well established and is worldwide the most installed battery in capacity – it is regularly used in off grid applications together with PV (Zipp, 2015). The energy density is about 25 to 30Wh/l in mobile battery packs and 50 to 75Wh/l in stationary versions with efficiencies of up to 70 to 75% (including battery converter). Stationary high-quality lead-acid- batteries have an average life expectancy of about 5 to 15 years, depending on temperature and state of charge, with a cycle life of about 2,000 cycles, in rare cases up to 7,000 cycles. The costs of this BESS are between 100 to 250€/kWh. In Europe, almost 100% of all industry used lead acid- batteries are recycled and the recovered lead can be used again for new battery production (ISEA, 2016).

Table 2: Overview of Lead-Acid- Batteries (ISEA, 2016) (Klima- und Energiefonds, 2016)

Lead-acid- battery	Today	+ 10 years
Efficiency charging – discharching including battery converter[12]	70 - 75%	73 - 78%
Energy density	50 - 75Wh/l	50 - 100Wh/l
Cycle life	500 – 2,000	1,000 - 4,000
Life expectancy	5 - 15 years (depending on temperature and state of charge)	8 - 20 years (depending on temperature and state of charge)
Depth of discharge	70%	80%
Self discharge	3 - 5% per month	2 - 4% per month
Load-related investment costs (converter)	150 - 200€/kW	100 - 150€/kW
Energy-related investment costs	100 - 250€/kWh	50 -150€/kWh
Specifications for installation location	Installation location needs to be ventilated – air flow rate depending on type of technology (sealed/vented); specification according to e.g. DIN EN 50272-2	
Advantages of the technology together with PV	Well established battery technology with long operating experience in stationary systems, low investment costs	
Disadvantages of the technology together with PV	Low energy density leads to higher space demand, air flow requirements not always easy to comply with in the battery room	

2.3.2 Lithium-ion- batteries (4V)

Li-ion batteries become more popular in all various applications. In early years, this battery type has mostly been used in mobile devices, like laptops, cameras or cellphones. More recently, this technology has been also introduced in electric mobility and stationary storage applications. Compared to Pb-acid- or NiCd-technolgies, Li-ion- batteries have much higher energy density (200 to 350Wh/l), and

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[12] In this case, a battery converter with 95% efficiency (per direction) has been assumed.

have therefore in mobile devices a clear competitive advantage, even though its higher specifc costs. There is not just one concept of this technology, but various combinations and compositions of electrolytes and electrodes, which bolster different features like life expectancy or safety. Due to these various compositions and ongoing intensive research this technology has still a huge development potential. Moreover, it is still not known which of these concepts will eventually become state-of-the-art technology for which application. It is to be expected, that this type of battery, together with Pb-acid- batteries, will be the most important technologies for most applications over the next 20 years (ISEA, 2016) (Klima- und Energiefonds, 2016).

At the moment, the energy density goes up to 350Wh/l. In optimal conditions, mostly depending on temperature and state of charge, the life expectancy can be higher than of Pb-acid- batteries with up to 5,000 complete cycles and 20 years. The used materials are always to be questioned, so it is worth making a short excursion and have a look at the market and development of lithium (ISEA, 2016). The world mine production of lithium was 31,700 tons in 2014 and increased slightly to 32,500 tons in 2015 (each without mining in U.S., because they avoid disclosing company proprietary data). At the moment, the biggest mining countries are Australia and Chile with 13,400 tons, respectively 11,700 tons per country in 2015. Due to higher demand the prices increased on average approximately by 10 to 15% from those of 2014. The worldwide reserves of pure lithium are estimated with about 14 million tons. (U.S. Geological Survey, 2016). Even Austria has 17 million lithium ore in Wolfsberg, were the mining production is expected to start in 2018 (Odrich, 2014). Lithium is not defined as a rare material, but still the demand for lithium is increasing continuously – although the markets vary by end-use and location, the following averaged global distribution is estimated: batteries, 35%; ceramics and glass, 32%; lubricating greases, 9%; air treatment and continuous casting mold flux powders, 5% each; polymer production, 4%; primary aluminum production, 1%; and other uses, 9%, whereas the lithium consumption for batteries has increased significantly in recent years (U.S. Geological Survey, 2016). It will become necessary to implement a complete recycle system, as with Pb-acid- batteries, including recovery of lithium. In order to keep prices stable mining companies, need security in planning in order to open new mines or increase mining efforts in already existing ones (ISEA, 2016).

Table 3: Overview of Lithium-Ion- Batteries (ISEA, 2016) (Klima- und Energiefonds, 2016)

Lithium-ion- battery	Today	+ 10 years
Efficiency charging – discharching including battery converter[13]	80 - 85%	85 - 90%
Energy density	200 - 350Wh/l	250 - 500Wh/l
Cycle life	1,000 - 5,000 (complete cycles)	2,000 - 10,000 (complete cycles)
Life expectancy	5 - 20 years (depending on temperature and state of charge)	10 - 25 years (depending on temperature and state of charge)
Depth of discharge	Up to 100%	Up to 100%
Self discharge	3 - 5% per month	<3% per month
Load-related investment costs (converter)	150 - 200€/kW	100 - 150€/kW
Energy-related investment costs	300 - 800€/kWh	150 - 400€/kWh
Specifications for installation location	At the moment, no specific requirements defined.	
Advantages of the technology together with PV	Long life expectancy, no requirements for installation location, high energy density (i.e. compact system), low costs of maintenance	
Disadvantages of the technology together with PV	High costs, humble experience with technology in this application (PV household), in case of an error risk of fire	

At the moment, Li-ion batteries are the most suitable battery type for residential households. Figure 7 shows that this BESS also experienced the highest growth rates in the last 5 years. Despite this fact, lead-acid- batteries are still the most important market in size with around 90% of the overall market share (right diagram). The overall

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[13] In this case, a battery converter with 95% efficiency (per direction) has been assumed

market volume was about 65 million U.S.$ in 2015 (pack[14] not included) with a 5% average growth per year from 1990 to 2015 (Pillot, 2015).

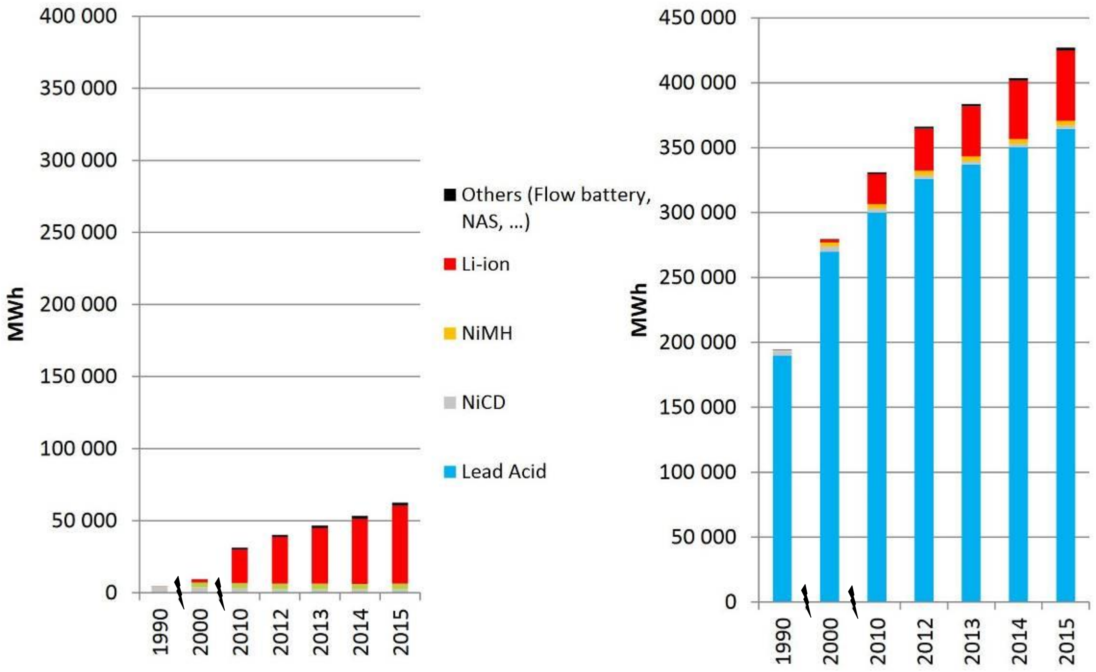

Figure 7: Worldwide Battery Market 1990 - 2015 (Pillot, 2015)

In 2015, the main applications for Li-ion- batteries (~55MWh) were automotive (~27%), portable PC's (~21%), cellphones (~17%), tables (~16%), e-bikes (5%) and others, like power tools, household devices, toys, etc. This shows, that the market for battery packs in households is still at the beginning and for the moment at global scale insignificant (Pillot, 2015).

Consequently, it is necessary to have a closer look at regional market developments for the type of application residential household. According to the yearly report from the higher technical school in Aachen from 2016, almost every second home PV installation has been equipped with a battery system in Germany in 2015. In the course of an incentive system in Germany from May 2013 to January 2016 about 34,000 battery systems have been installed together with a PV system, a cumulated

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[14] Pack: cell, cell assembly, battery management system, connectors – power electronics (DC DC converter, invertors, …) not included.

storage capacity of 200MWh has been added into the low voltage grid. Li-ion- battery systems squeezing Pb-acid- batteries literally out of the market in this segment – at the beginning of 2013 almost 70% of all batteries were Pb-acid- systems, whereas 2.5 years later its share reduced to 10%. Figure 8 shows the actual ratio between these two battery types over the last quartals (Badeda, et al., 2016).

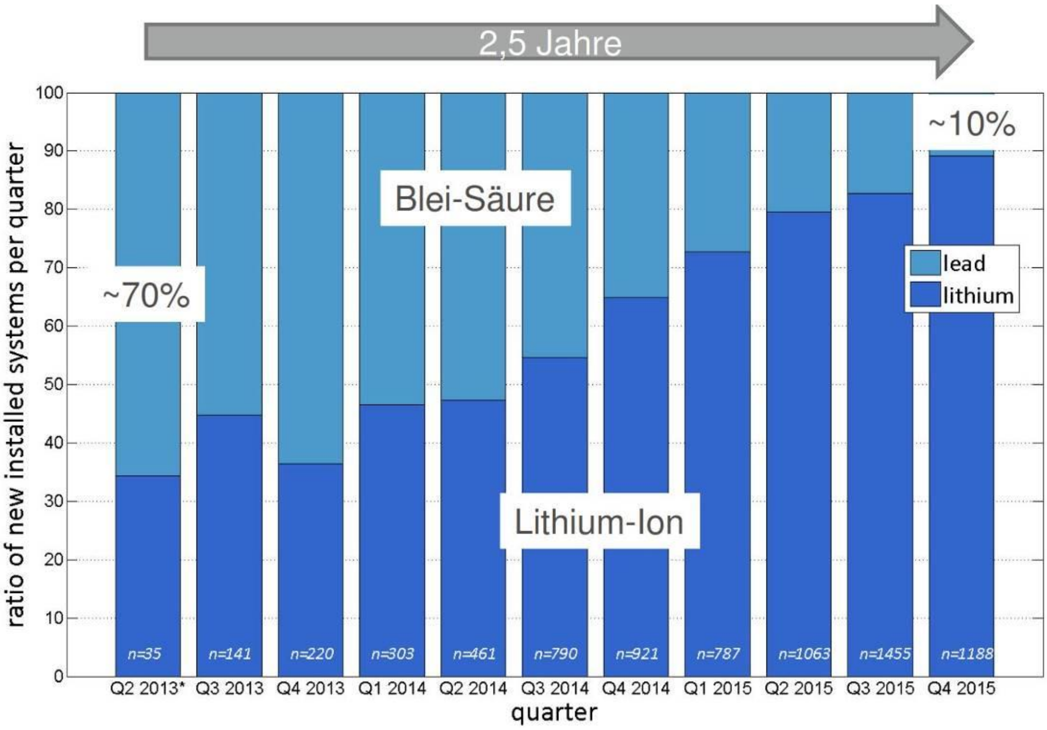

Figure 8: Ratio of Newly Installed Battery Systems from Q2/2013 to Q4/2015 (Badeda, et al., 2016)

This development towards lithium-ion- systems is also influenced by the fact, that the average decline in costs was about 20% per year between 2013 to 2015, whereas lead-acid- systems experienced a decline of 7% per year in the same period (see Figure 9). In the long run it is expected, that the reduction in prices will go on, most importantly, because of the market entry and huge investments of big companies like Tesla, Daimler, VW, etc. (Badeda, et al., 2016).

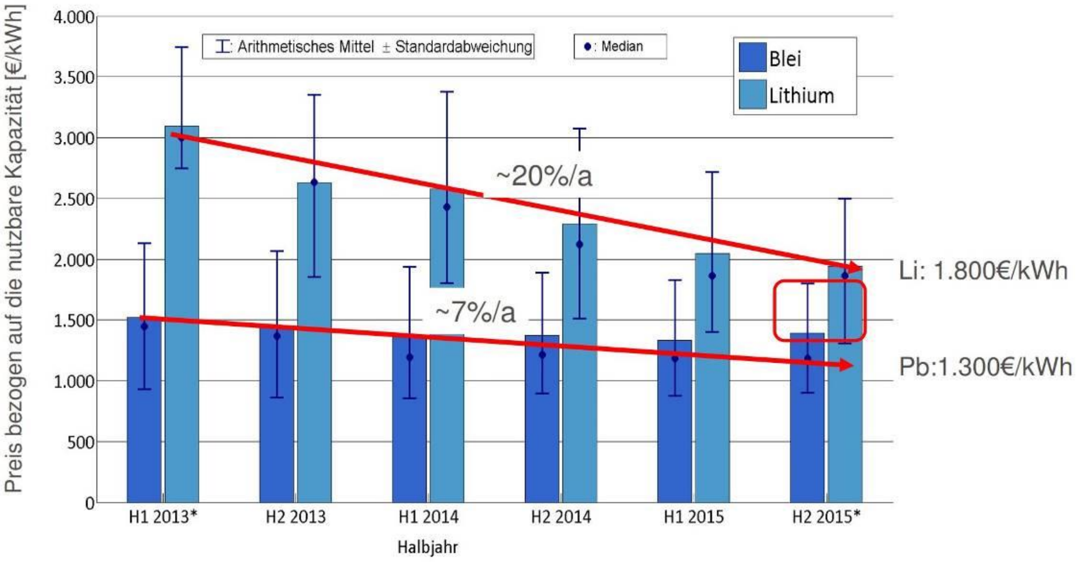

Figure 9: Development of Prices per kWh of Lead-Acid- and Lithium-Ion- Systems (Badeda, et al., 2016)

Latest studies from pv magazine illustrate, that the prices further declined in Germany between May and October 2016. The decrease in this short period was up to 6%, depending on the size of the battery system (pv magazin, 2016).

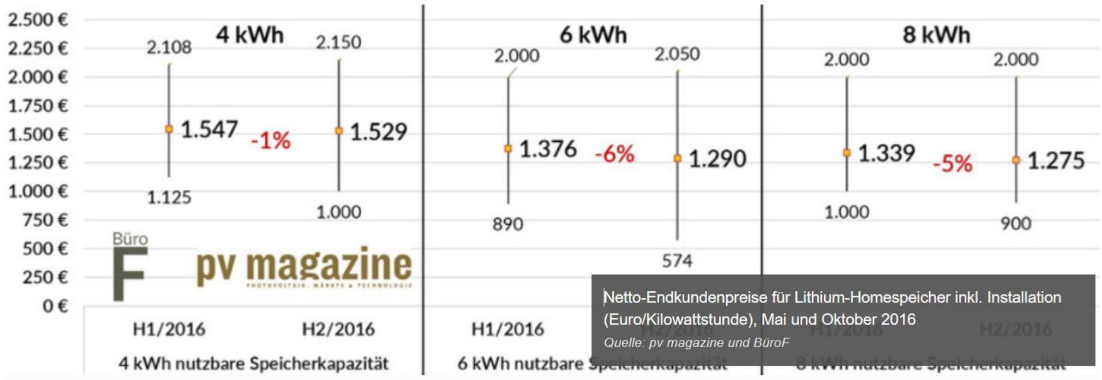

Figure 10: Prices per kWh of Lithium-Ion- Systems incl. Installation between May and October 2016 (pv magazin, 2016)

The most expensive part of a Li-ion- battery system is the cell itself, therefore the historical development of the cells and the degradation of costs can be taken as benchmark. In Figure 11, a possible future scenario from the technical school of

Aachen, has been pictured. Is is predicted, that lithium-ion batteries for e-mobility will show the strongest decline in costs, due to its expected market size. In the long run, its production volume and the known economy-of-scales effect will bring the prices of Li-ion- systems in this sector close to the price of Li-ion- cells. Hence, this process will also influence Li-ion- MW- as well as BES- systems. Currently the pricing of BESS (battery including cells, battery management system, casing, etc.) is still influenced by high production costs as well as relatively high margins for the distributer/manufacturer; on top of that they also pass on the historical costs of research and development for this application to the customer. However, with higher production volumes, prices will continue to decrease on the basis of technically mature systems and streamlined production. Nevertheless, a premium price for PV-BESS will remain compared to the high quantities of batteries in the e-mobility (Aundrup, et al., 2015).

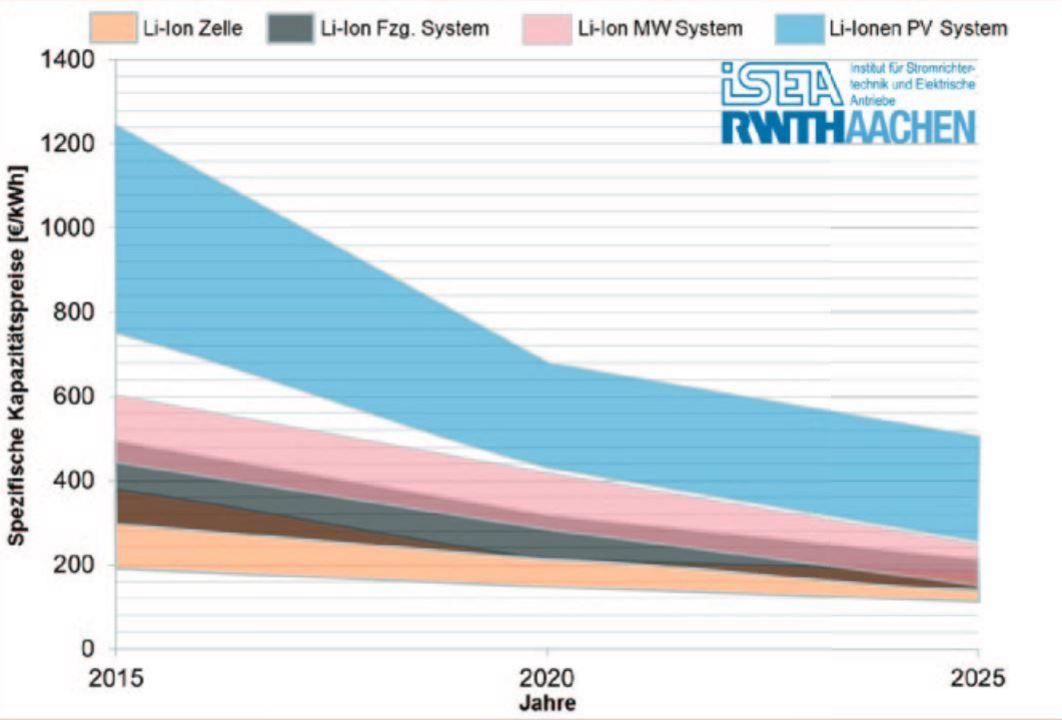

Figure 11: Forecast of the Price Development of Li-ion- cells, E-mobility, PV-BESS and MW systems (Aundrup, et al., 2015)

Another study from the technical school of Aachen (multi-selection was possible) further indicates, that the costs per kWh are not the most important factor for decision making. More than 80% of the people in this survey voted for “becoming independent against increasing energy prices in the future” and “own contribution for the transformation of the energy system”; around 60% additionally chose “interested in the technology”; whereas, just around 25% voted for “backup in case of a blackout”, 20% “safe investment” and/or around 15% “cessation of FiT” (Badeda, et al., 2016).

2.4 Degree of Self-Consumption and Self-Sufficiency

As it has been pointed out in the last chapters, due to the support of incentive systems, higher volumes and more efficient processes along the value chain, the costs of PV as well as battery systems are continuously decreasing. The reduction and omission of incentive systems in the countries over time additionally forced the industry to lower prices. Since the price of a self-produced kWh for residential households is equal or lower than the retail prices for electricity (including grid costs, taxes, levies and other charges, etc.) for the end consumer in some countries the idea of self-consumption (c) and self-sufficiency (s) became more important. Whereas in former times, the future prosumer tried to use the maximum available installation area (rooftop, field, etc.) in order to get the maximum possible incentive, the ongoing development goes towards higher degree of self-consumption and self-sufficiency in order to minimize the amount of purchased kWh from the utility. Consequently, the decreasing overall costs for BESS strengthen this development further. This is true for markets with high retail prices for electricity for the end consumer, comparatively smaller selling/incentive prices than retail prices and a certain incentive system in place for batteries.

How is the degree of c and s defined? And what are the most useful values for a residential household at the moment? There is a consent about the definition, but in the literature, exists no common rating of c or s – the factors of influence from technical, economical and even regional political point of view are too wide spread. Various studies focus on quantifying c or s within a given system (S. Quoilin et al., 2016). According to the study of R. Velik from the CTR in Villach Austria, the degree of self-sufficiency varies between 30 to 66% in winter and 48 to 99% in summer, depending on the battery size (0-32kWh) (Velik, 2013). Similar results have been stated from Truong et al. for German housholds, in which a 7kWh battery increases s from 38 to 65% (Truong et al., 2016). Weniger et at. found that a battery of 1kWh per MWh of yearly consumption with a PV plant of 1kWp/MWh achieve approx. 54% rate of self-sufficiency. PV-BESS with more than 70% of s become prohibitively large (Weniger et al., 2014).

An alternative and/or additional way to increase c and s, except the installation of a BESS, is demand side management (DSM) through load shifting. Many studies regarding this topic with various results have been carried out in recent literature. According to R. Thygesen and B. Karlsson DSM results only in an increase of 7% of the degree of self-sufficiency (R. Thygesen, 2015). Whereas M. Castillo-Cagigal et al. found in their studies an increase of s from 30.9 to 56.9% without BESS and up to 76% including a BESS (M. Castillo-Cagigal et al., 2011). Demand side management including demand response (tries to adjust the demand for energy rather than the supply) together with load-variable tariffs, smart meters and grids will become more important for balancing future grid systems consisting mainly of fluctuating renewable energies sources (Agricola, 2011). Due to limitations of scope this specific development will not be further analysed in this master thesis and gives opportunity for further research in this topic.

Hence, the following general definitions of c and s and assumptions have been concluded:

2.4.1 Degree of self-consumption (c)

The degree of self-consumption describes the proportion of the generated solar current, which is either used simultaneously by the consumers or to charge the battery. The higher the degree of self-consumption, the less solar power is fed into the grid.

For an easier comparision and better evaluation of the degree of self-consumption in this master thesis, a classification taken from the Sonnenklar calculator from PVAustria and NFSol will be used (PV Austria, NFSol, 2016):

> 80%: optimum (at the time of this paper)
56 – 80%: very good degree of self-consumption
31 – 55%: good self-consumption, but still possible to improve
< 30%: average degree of self-consumption without battery

2.4.2 Degree of self-sufficiency (s)

The degree of self-sufficiency indicates the share of the electricity consumed by the photovoltaic storage system. Either the simultaneous direct matched demand of the generated solar current or the discharge of the battery storage contributes to this. The higher the degree of self-sufficiency, the less energy is drawn from the power grid.

For an easier comparision and better evaluation of the degree of self-sufficiency in this master thesis, an own classification established from several studies will be used (S. Quoilin et al., 2016; Velik, 2013; Truong et al., 2016; Weniger et al., 2014):

> 60%: optimum (at the time of this paper)
46 – 60%: very good degree of self-sufficiency
31 – 45%: good self-sufficiency, but still possible to improve
< 30%: average degree of self-sufficiency without battery

Following these concepts, 100% self-sufficiency (for example full off-grid operation) at a given household with a certain set of behaviours would solely be possible with an unreasonable and unfeasible oversized PV-BESS. The very last percents of s will be much costlier than at any lower level of s. It would be necessary to dimension the whole system in a way to even out extensive periods of rain/fog/no sun (over weeks) within the “normal” set of behaviours in order to avoid any blackouts. The dregree of c is important to indicate how much of the produced energy is directly used (or via charging the battery). It does not state how much of the overall demand of the household is covered. Consequently, a very small PV-BESS could already lead to 100% of c, just covering a minor amount of the total energy demand of the household. This indicates, that a prosumer first and foremost wants to maximize the degree of self-sufficiency in order to be as independent from the utility and from possible future energy price escalations as possible. It is further assumed, that the prosumer wants to achieve a high s in the best financially and economically way, which again is depending on the degree of self-consumption. The higher the c in a system, the better the ratio of energy production and energy demand/consumption of the household. Obviously, it would be possible to oversize the PV-BESS in a certain household (with a certain demand) in order to reach a higher s, but this would increase the initial investment costs of the overall system. As a result, the dimension and configuration of an "optimal" PV-BESS must consider and try to attempt a maximum in c as well as s, always keeping the feasibility of the overall system in mind (e.g. initial investment, life expectancy, maintenance, etc.).

That is why the following *additional assumptions* has been set in place:

- Each kWh, which reduces grid export (by DMD of own electricity production from PV-system or energy charging the battery), is beneficial for the household (= high self-consumption favourable).
- Each kWh, which lead to more energy autarchy of grid import (by DMD own electricity production from PV-system or energy discharging from battery), is beneficial for the household (= high self-sufficiency favourable).
- At the current state 100% self-sufficiency is economically not feasible. As a consequence, in this master thesis the attempt is to come as close (or higher) as possible to the set optimum of both key figures. It is not the aim to maximize one, at cost of the other, due to the mentioned reasons above. So, at the moment of this paper the (technical and economical) optimum target has been set at:

$$self\ consumption = c => 80\%\ and\ self\ sufficiency = s => 60\%$$

2.5 Application: PV - Battery Energy Storage System

After describing and selecting an appropriate PV technology and battery system, the next important step is to connect both features in one application – PV-BESS. In chapter 2.3., it has been said, that e-mobility could become the biggest market for batteries in the long run. But in the most recent developments it appears, that e-mobility needs more time in the market. For example, in Germany more batteries for

PV systems (2015: about 18-20,000 batteries; 2016: about 15,000 batteries without Q4) have been installed than for e-mobility (2015: 12,363 e-cars, 2016: 11,410 e-cars) in the last two years. For both sectors are incentives systems in place, the smaller one for PV systems was and will most probably be completely used up again in 2017, whereas the multi-billion one for e-mobility hasn't been needed by far (Enkhardt, 2016).

Hence in the short term, PV-BESS may become the most important market for battery systems with learning effects for other applications. Since 2014 batteries for PV-BESS are getting subsidized in some states in Austria as well. As long as the *additional assumptions* from the previous chapter 2.4. are valid, the basic objective for an owner of a PV-BESS (residential or commercial) is to increase the direct matched demand (DMD), hence self-consumption ("direct use" in Figure 13) and self-sufficiency ("self-coverage" in Figure 13). Figure 12 shows a simplified graphical presentation of the energy distribution in a PV-BESS (Kathan, 2016). For example, a surplus of energy (more production of the PV system than demand in the house at a certain time) during a sunny day can be stored in the battery for latter use. So, this stored amount of energy does not need to be imported from the grid later on. A well-designed PV-BESS maximizes DMD and, therefore, reduces the amount of imported/exported electricity from/into the utility grid. Consequently, the owner is going to save money – again, as long as the costs per kWh from the PV-BESS are smaller than from the utility. It is also possible to connect many batteries to a central storage (e.g. multi-family house, apartment building, etc.) in order to increase the DMD even more.

An objective of the utility/grid operator could be to reduce or flatten the fluctuations of the grid. Once all systems are connected via e.g. smart metering, many PV-BESS (residential, commercial and industrial) could be even integrated into a virtual storage power plant (e.g. divided by local area) in order to fulfil certain tasks – decoupling of supply and demand; energy buffer for peak currents; stability of the grid; balance deviations from forecasts. Last but not least, an objective of the government/utility could be the reduction of exported (feed-in) electrical energy into the grid (by charging the batteries) in order to diminish the overall costs of the FiT program (Klima- und Energiefonds, 2016). This may indicate, that a further positive development of PV-BESS is going to be accepted or even welcomed by all involved parties.

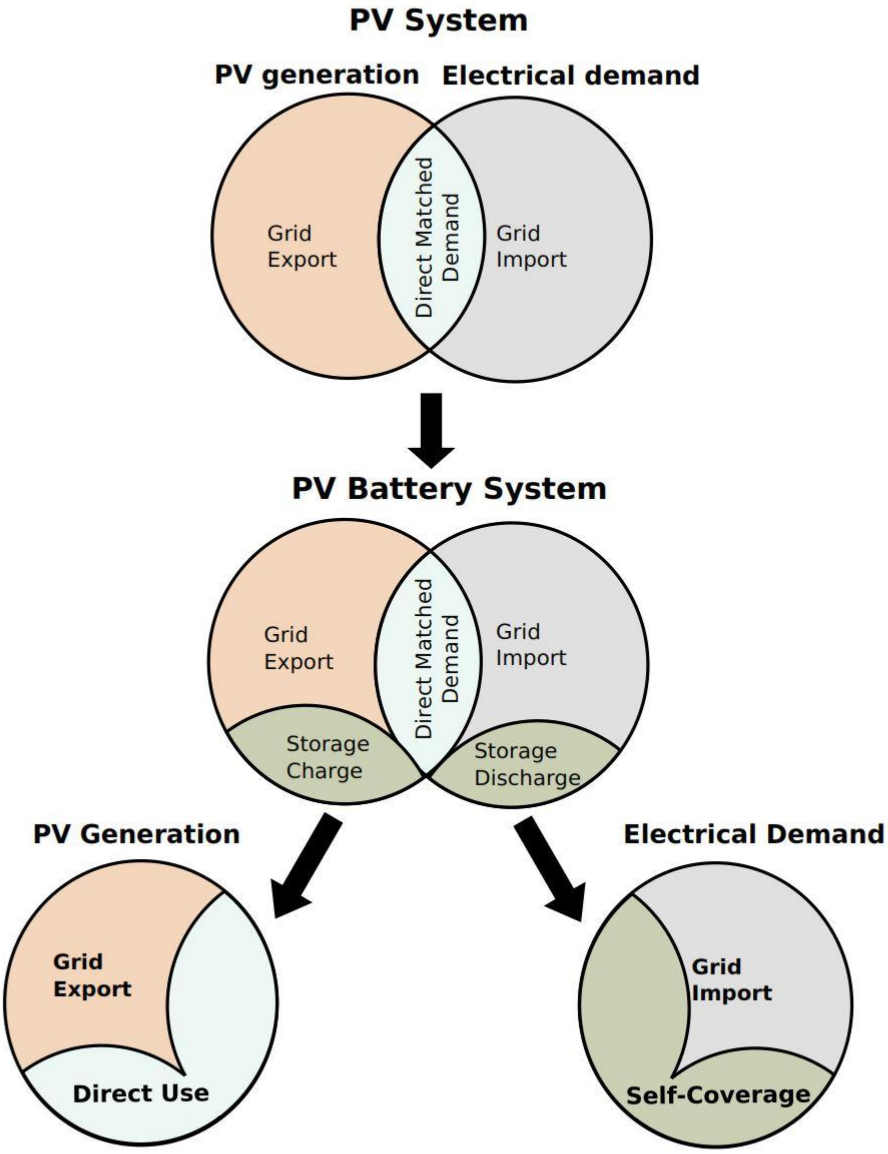

Figure 12: Simplified Energy Distribution within a PV-BESS (Kathan, 2016)

Figure 13 gives a basic overview of a PV-BESS and its necessary devices. There are different types of construction of PV-BESS in the market. All-in-one systems (PV inverter, charge controller and battery in one single housing) must be installed together and are limited to single manufacturers/suppliers. Modular systems are more flexible and can be integrated step-by-step in a household and may allow also different types and brands. According to the electrical connection scheme, there are two main configurations – DC or AC coupled. A DC coupled topology does not need its own DC/AC conversion – it uses the one from the PV inverter for it –, which is a cost advantage compared to the AC coupled system. But an AC coupled system offers much greater flexibility, because it has its own AC/DC conversion unit. Hence, in case of retrofitting of an existing PV system this topology is preferred (Kathan, 2016).

Figure 13 illustrates a AC coupled system – the PV generator (1) and PV inverter (2) form the PV system. The full-sized battery system with its battery management system (3), charge controller (4) and energy management system (5) represent the BESS. The imported and exportet energy, which runs over the grid connection, is measured by the energy meter (6). Last but not least, the household has various electronic and domestic appliances, like lighting, TV, fridge, hair dryer, etc. (7).

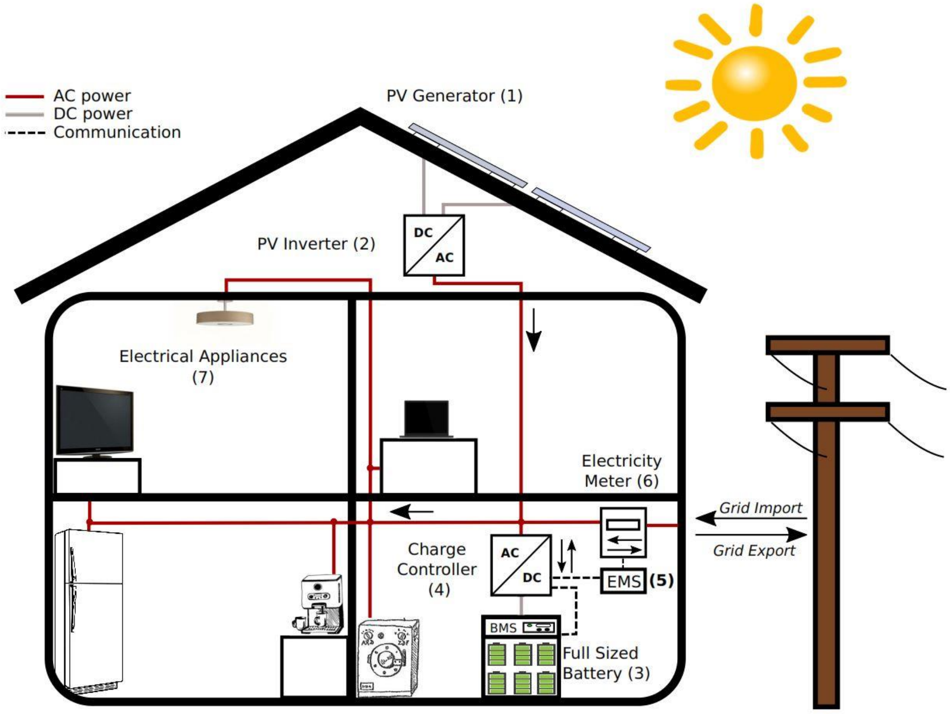

Figure 13: PV - Battery Energy Storage System - General Overview (Kathan, 2016)

In the following all numberd devices of Figure 13 will be described in more detail:

(1) PV Generator

The PV modules are the so-called PV generator. The modules are generating electric power by converting light into electricity using crystalline or amorphous solids with the photovoltaic effect.

(2) PV Inverter

The inverter transforms the electric power as direct current (DC) from the PV generator to common household alternating current (AC). Additionally, it optimizes the system performance with its “maximum power point” (MPP), a combination of voltage and current at which the PV modules – depending on temperature and irradiation – operate at peak performance.

(3) Full Sized Battery (including Battery Management System)

If the energy production of the PV generator is greater than the energy demand of the household at a certain time, an energy surplus arises. The battery is a storage device, which accumulates this energy surplus of a system for latter use. As it has been mentioned in chapter 2.3, there are various types and technologies of batteries in research as well as on the market.

A battery system also includes an electric circuit, better known as battery management system (BMS). A well-working BMS ensures a long and safe operation of the battery. A battery itself contains many cells, which are interconnected to each other. Owing to the production process, each cell has slightly different specifications, e.g. energy capacity, depth of charge/discharge, etc. The BMS monitors the operating data of all cells and balances the temperature or controls and limits the state of charging and discharging of each cell (Energie Wissen, 2016).

(4) Charge Controller

The information from the BMS is used in the charge controller for proper charging and discharging of, and preventing damage to, the battery. It regulates the actual current for this and provides the right amount of power for the energy management system (EMS – see next paragraph). A DC coupled system just uses a DC/DC converter in order to regulate the voltage level to a required amount. In AC coupled systems (like in Figure 14) an additional DC/AC converter at inverter stage must be included. In order to change the voltage level in such a system, often an addtitional AC/AC transformer is necessary (Kathan, 2016).

(5) Energy Management System (EMS)

An EMS monitors the energy flows of the building, checks the operating data of the PV system and the state of charge of the battery. For example, it monitors the production of the PV system and the current demand in the building. Excess energy will be stored in the battery – if there is still capacity left – or it will be exported (feed-in) into the grid.

More sophisticated EMS not just observe the whole building in order to increase c or s, but also use external information, like weather forecasts, to optimize the complete system. Moreover, it can be connected to external servers, which collect many of these PV-BES- systems to a virtual storage power plant in order to stabilize the grid, harmonize peak currents, etc. (Energie Wissen, 2016).

(6) Electricity Meter

The electricity meter is a sensor, which measures the imported or exported power between the building (e.g. houseowner) and the grid (e.g. utility company). Standard (old) meters just counted the power unidirectional, whereas new, smart meter devices provide a bidirectional measurement. Latter is necessary to exchange information between both parties, like how much is the actual energy production of the PV system or how is the state of charge of the battery, or even fulfil grid related tasks (e.g. as a virtual storage power plant) (Kathan, 2016).

(7) Electrical Appliances

This term refers to all different domestic and elelctrical devices in a building, which need electricity for operation, like lighting, computer, electical heater, fridge, vacuum cleaner, etc.

Chapter 3: Methodology

This chapter shortly describes the course of events, including how to find appropriate literature and how to do structural research. Furthermore, based on all information from the previous chapters, an adequate tool for analyzing the available data will be chosen.

Important sources and up-to-date information for the literature research has been found in the databank application “TU Wien Universitätsbibliothek” via “WebVPN”. This university catalog grants access to books and journals (Aleph, etc.) as well as most recent e-books, e-journals from TU Wien and other university databanks. Additionally, current reports from respectable authorities, institutes and agencies have been selected, like Frauenhofer, ISEA, IEC, IRENA, RWTH Aachen, EPIA, and many more. Information from Austria has mainly been gathered from TU and FH Technikum Wien, bmvit and PVAustria. Very accurate information and data about batteries has been found at “Speichermonitoring” for Germany and “Speicherinitiative” for Austria, whereas the German data is more precise because of the fact, that all PV- as well as BES- systems, which are granted an incentive in Germany, must be registered. In Austria, all available data has been individually carried together by FH Technikum Wien, utilities, etc.

As theoretical framework of this master thesis and its empirical analysis the *ceteris paribus* clause has been chosen. This Latin phrase, with the meaning “other things equal”, is used in economics, in which it is regularly necessary to simplify wordings and descriptions of economic results (Schlicht, 1985). “All factors not explicitly considered as variables are assumed to be fixed within an argument. This clause is used, explicitly or implicitly, throughout economics.” (Schlicht, 1985, page 3).

In a next step, it is important to describe the acquired dataset. For the case study of this paper the qualitative MBS (“Multifunktionales Batteriespeichersystem”) dataset from R. Sterrer and W. Prüggler has been chosen. In a project consortium[15], they compiled load profiles for four different Austrian households (HH) for an entire year:

- double income no kids' household (DINCI HH) with a total energy demand of 3,233.87kWh.
- pensioners' household (P HH) with a total energy demand of 3,835.84kWh.
- family with two school-age kids, both parents working household (FSKNPL HH) with a total energy demand of 5,507.62kWh.
- family with two non-school kids, one parent in parental leave household (FNSKPL HH) with a total energy demand of 5,780.79kWh.

Individual patterns of behaviour for each family have been put together, like different times of cooking, working hours, holidays, etc. In this dataset, all relevant climate data (like average duration of lights, etc.) has been taken from the area of Wiener Neustadt. For more detailed information, please see Appendix A. As a result, this dataset contains hourly kWh of consumption per household. Together with the technical data of the chosen PV-BES- system a qualitative analysis and comparison of the information will be carried out. So, significant equalities and inequalities of certain behaviour patterns can be identified. More details to this dataset and its individual set of behaviour will be given in the next chapter.

Finally, the aggregated data will be economically analysed by using sensitivity analyses as mathematical model. "Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs" (Vasileios Karyotis, 2016, page 173). So, it is possible to change certain input variables (e.g. from -10 to +10) in order to see how, and to which extant, it is going to influence the resulting outcome (Saltelli, 2002). As a result, certain patterns of behaviour will be identified, which are positive or negative for the performance of the complete PV-BESS. Moreover, due to individual optimization an adequate PV-BESS for each of the four households will be proposed.

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[15] Project consortium was composed of FH Technikum Wien – Institut für Erneuerbare Energie, EVN AG, ATB- Becker, KEBA AG, Cellstrom GmbH und der TU WIEN – Energy Economics Group.

Chapter 4: Empirical Analysis

This chapter is about the calculation, analysis and findings of the underlying case study with the four different households of the MBS dataset. As already mentioned, all details of each set of behaviour as well as the hourly electricity demand of each household can be seen in Appendix A. For a better understanding of the findings and conclusions of this chapter, the results of the underlying, self-compiled calculations (in Excel) can be requested from the author. In order to answer the research question of this mater thesis, the households need a local energy production – PV system – as well as a storage device – battery system.

Following *additional assumptions* (see chapter 2.4. for more detailed information) are necessary to know for the following part:

- Each kWh, which reduces grid export (by DMD of own electricity production from PV-system or energy charging the battery), is beneficial for the household (= high self-consumption favourable).
- Each kWh, which lead to more energy autarchy of grid import (by DMD own electricity production from PV-system or energy discharging from battery), is beneficial for the household (= high self-sufficiency favourable).
- At the current state 100% self-sufficiency is economically not feasible. As a consequence, in this master thesis the attempt is to come as close (or higher) as possible to the set optimum of both key figures. It is not the aim to maximize one, at cost of the other, due to the mentioned reasons above. So, at the moment of this paper the (technical and economical) optimum target has been set at:

$$self\ consumption = c => 80\%\ and\ self\ sufficiency = s => 60\%$$

Chapter 4:

Empirical Analysis

4.1 Design and Calculation of the PV-BESS

For this the following PV-BESS has been chosen:

4.16kWp PV rooftop system in Wiener Neustadt, Austria (no shadings):

- 16 x Trina TSM-260 PD05 Modules (Trina Solar, 2016)
  - Nominal power: 260W[16]
  - Efficiency: 15.9%
  - Module dimensions: 1,650 x 992 x 35mm [A]
- 1 x Fronius Symo Hybrid 4.0-3-S (Fronius, 2016)
  - Nominal power: 4kWp
  - Max. efficiency: 97.9% (PV – grid)
  - Max. efficiency: >90.0% (PV – battery – grid)
- 1 x Fronius Solar Batterie 4,5kWh (Fronius, 2016)
  - Technology: LiFePO4
  - Nominal capacity: 4.5kWh
  - Depth of discharge: 80%
  - Usable capacity: 3.6kWh (80% of 4.5kWh)
  - Cycle stability: 8,000 cycles[17]
  - Cycle life: >20 years[18]
- 1 x Fronius SmartMeter

The interactive map of PVGIS gives the yearly sum of global irradiation on a horizontal and optimally inclined surface. The data contains an average of the years between 1998 till 2011; all values are given in kWh/m^2. For this paper, the solar irradiation data for a selected module inclination and orientation has been taken, in order to get daily

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[16] Standard Test Conditions (STC): light intensity is 1000 W/m2, with a spectrum similar to sunlight hitting the earth's surface at latitude 35°N in the summer (airmass 1.5), cell temperature 25 °C.

[17] At 23° ambient temperature (Fronius, 2016).

[18] At 23° ambient temperature (Fronius, 2016).

profiles of the average global irradiance for a certain location in an intervall of 15 minutes in W/m^2 (Huld T., 2012).

Further important assumptions (Huld T., 2012):

Location	Wiener Neustadt, Austria (no shadings)
Optimal alignment	0° (south)
Optimal inclination	35°

Estimated losses due to temperature and low irradiance

η_T = 8.0% (using local ambient temperature)

Estimated loss due to angular reflectance effects

η_R = 2.9%

Combined PV-system losses

η_S = 19.6% (incl. 10% other losses from wiring, MPP, inverter, transformer, etc.)

The resulting averaged, yearly irradiation database has been used to calculate the averaged, yearly production of the 4.16kWp PV system in Wiener Neustadt. In order to be able to compare the production and demand curves correctly, the irradiation data with an interval of 15 minutes had to be adjusted to hourly values. Using the specifications of the data sheets (Trina and Fronius) together with the estimated losses of the temperature, low irradiation, angular reflectance as well as the PV-system, the result is an averaged, yearly production database.

$$\boldsymbol{E_{PV} = A * r * H * PR}$$

$$E_{PV} = \text{ electrical energy produced by the PV system } (kWh)$$

$$A = \text{ total solar panel area } (m^2)$$

$$r = \text{ solar panel yield or efficiency} (\%)$$

$$H = \text{ annual average solar radiation on tilted panels } (\text{shadings not included})$$

$$PR = \text{ performance ratio, coefficient for losses } (\text{range between } 0.5 \text{ and } 0.9)$$

$$A = length * width\ of\ module\ in\ meter * amount\ of\ modules$$
$$= 1.65m * 0.992m * 16 = 26.1888m^2$$

$$r = \frac{nominal\ power\ of\ one\ module}{A} = \frac{0.26kW}{1.6368m^2} * 100 = 15.88\%$$

$$H = 1{,}372.455 \frac{kWh}{m2}\ (Wiener\ Neustadt, PVGIS)$$

$$PR = (1 - \eta\mathrm{T}) * (1 - \eta\mathrm{R}) * (1 - \eta\mathrm{S}) = 0.718$$

$$\boldsymbol{E_{PV} = 26.1888m^2 * 15.88\% * 1,372.455 \frac{kWh}{m^2} * 0.718 = 4,100.67kWh/a}$$

The result of E_{PV} means that the 4.16kWp PV rooftop system in Wiener Neustadt, Austria produces in average 4,100.67kWh per year. Hence, this will model the production curve for each of the four households.

In a next step the usable capacity of 3.6kWh of the Fronius battery (4.5kWh nominal capacity * 80% depth of discharge) will be integrated in the PV-system and consequently, charged when the production > demand (until the battery hits its maximal capacity of 3.6kWh) and discharged when demand > production of the PV-system (until the usable capacity of the battery is completely discharged). Is the first case reached (battery full), each additional kWh produced (energy surplus) will be exported/fed into the grid (grid export). In the latter case (battery empty), each additional kWh required (energy deficit) will be imported/drawn from the grid (grid import).

Battery nominal capacity (B_{NC})

Maximal capacity of the battery, taken from the data sheet of the battery.

Depth of discharge (DoD)

The DoD describes how deeply the battery should be discharged (in %).

Battery usable capacity (B_{UC})

The usable capacity of a battery is the product of the nominal capacity and the depth of discharge. If the charging and discharging of the battery is kept within this limit, it will have a positive effect on the life expectancy of the battery (in kWh).

$$\boldsymbol{B_{UC} = B_{NC} * DoD}$$

$$\boldsymbol{B_{UC} = 4.5kWh * 80\% = 3.6kWh}$$

For example, the next Figure 14 shows Tuesday, 6th April 20XX of the pensioner's household. In the description of the pensioner's household it is mentioned, that every Tuesday the couple has an additional cleaning session, in the morning as well as in the afternoon - washing machine & dryer 2x, vacuum cleaner 3x, light bath 6h (please see Appendix A). This can be seen at the extra increase in demand (red line) from 8-10AM. Again, at 2PM in the afternoon an additional, but smaller rise in demand is visible. In the first case the high demand discharges the battery completely (green line) and also outweighs the electricity production of the PV-system (dark blue line), therefore an extra supply of the grid is necessary (purple line). In the latter case the cleaning session could be entirely absorbed by the PV production, even more because of the fact that the battery has been already fully charged at that moment in time. The excess production could be even fed into the grid (light blue line). Also, the midday peak in demand caused by cooking, led to an import from the grid. Last but not least the higher evening demand from 5-7PM, due to dinner, TV, etc. together with the decreasing electricity production, starts to discharge the battery. As the evening demand of the two pensioner's is not very intense and/or long in time, the remaining load of the battery can be used again for the next mornings increase in demand. This shows already, that the behaviour and therefore the load demand curve of the pensioner's household fits quite well together with the specifications of the chosen PV-BESS.

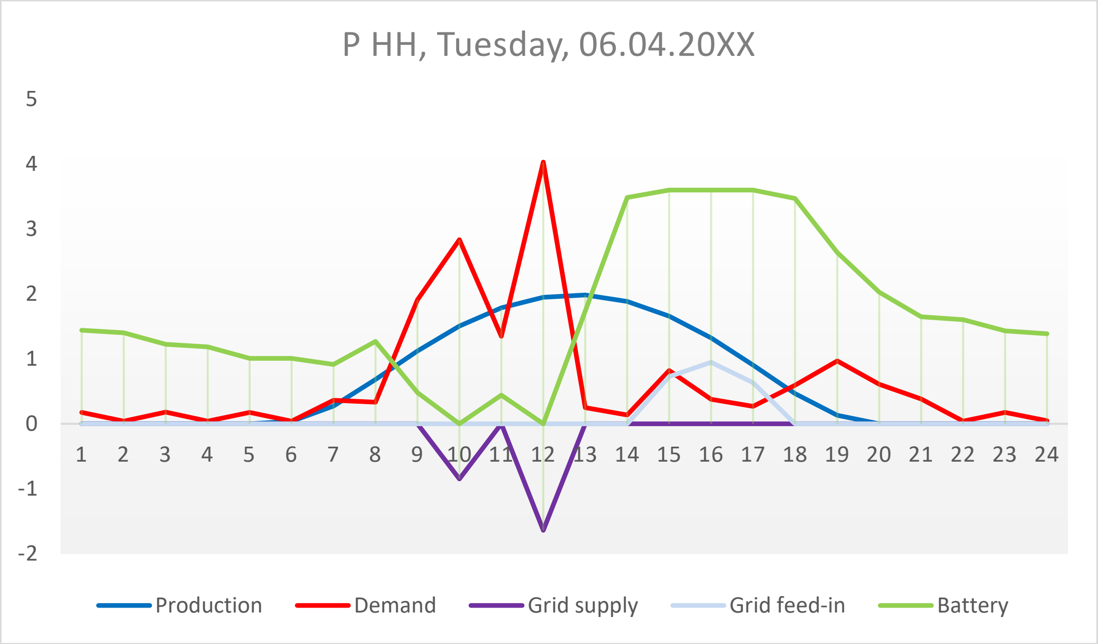

Figure 14: Example of a Tuesday in the Pensioner's Household (06.04.201XX)

Consequently, it is possible to calculate, analyse and compare the key figures (like degree of self-consumption and self-sufficiency, cycle stability and duration/life expectancy of battery, etc.) as well as the pattern of behaviour of each of the households and find significant similarities or deviations, which might have an impact on the performance of the PV-BESS.

Energy PV-system (E_{PV})

Total of energy production, which will be produced of the PV rooftop system over the whole year (in kWh).

Energy demand (E_D)

Total of energy demand of each of the four households (load profiles in Appendix A) over the whole year (in kWh).

Energy grid import (E_{GI})

Total of energy, which has to be drawn from the grid in times of energy deficit in the PV-BESS over the whole year (in kWh).

Energy grid export (E_{GE})

Total of energy, which has to be fed into the grid in times of energy surplus in the PV-BESS over the whole year (in kWh).

Energy direct matched demand (E_{DMD})

Total of energy demand, which directly matches production (without battery) in the PV-BESS over the whole year (in kWh).

Energy battery machted demand (E_{BMD})

Total of energy demand, which directly can be taken from the battery (no direct matched demand) in the PV-BESS over the whole year (in kWh).

Energy self-consumption total (E_{CT})

Total of produced energy, which can be overall directly used in the PV-BESS over the whole year (in kWh).

$$\boldsymbol{E_{CT} = E_{DMD} + E_{BMD}}$$

Degree of self-consumption (c) (further details see chapter 2.4.1.)

For an easier comparision and better evaluation of the degree of self-consumption in this master thesis, a classification taken from the Sonnenklar calculator from PVAustria and NFSol will be used (PV Austria, NFSol, 2016):

> 80%: optimum (at the time of this paper)
56 – 80%: very good degree of self-consumption
31 - 55%: good self-consumption, but still possible to improve
< 30%: average degree of self-consumption without battery

Degree of self-sufficiency (s) (further details see chapter 2.4.2.)

For an easier comparision and better evaluation of the degree of self-sufficiency in this master thesis, an own classification established from several studies will be used (S. Quoilin et al., 2016; Velik, 2013; Truong et al., 2016; Weniger et al., 2014):

> 60%:	optimum (at the time of this paper)
46 – 60%:	very good degree of self-sufficiency
31 – 45%:	good self-sufficiency, but still possible to improve
< 30%:	average degree of self-sufficiency without battery

$$\boldsymbol{c = self\ consumption}\ (\%) = \frac{\boldsymbol{E_{CT} + E_{BC}}}{\boldsymbol{E_{PV}}}$$

$$\boldsymbol{s = self\ sufficiency}\ (\%) = \frac{\boldsymbol{E_{CT} + E_{BD}}}{\boldsymbol{E_{D}}}$$

$$E_{DMD} = \ energy\ direct\ matched\ demand\ (kWh)$$

$$E_{BC} = \ energy\ battery\ charged\ (kWh)$$

$$E_{BD} = \ energy\ battery\ discharged\ (kWh)$$

$$E_{PV} = \ energy\ PV\ generated\ electricity\ (kWh)$$

$$E_{D} = \ energy\ demand\ (kWh)$$

Cycle stability (CS) of the battery

(Theoretically) The maximum amount of complete cycles (complete charging and discharging cycles within the usable capacity of the battery), that the battery can withstand before it starts to reduce its performance. This value is given in the data sheet of a battery. The maximum cycle stability is just reachable under ideal conditions, like ambient temperature, depth of discharge, etc.

Duration/life expectancy (LE) of the battery

The life expectancy of a battery is mainly depending on the cycle stability. It can be positively influenced by keeping the ambient temperature constant around 23° and staying in the usable capacity of the battery (depth of charge).

In a next step the four different households will be separated into two groups – households with two residents and households with four residents. In order to have a better basis for comparision the total demand of each group will be matched.

Category 1: DINCI HH (actual 3,233.87kWh) and P HH (actual 3,835.84kWh)

➔ Total averaged energy demand of Category 1: **3,534.86kWh per year**

Category 2: FSKNPL (actual 5,507.62kWh) and FNSKPL (actual 5,780.79kWh)

➔ Total averaged energy demand of Category 2: **5,644.21kWh per year**

The resulting matrix of these key variables for all four households is summarized in the following:

Table 4: Summary of Key Figures of each Household (Base Scenario) (own illustration)

	Category 1		Category 2	
	DINCI HH	P HH	FSKNPL HH	FNSKPL HH
PV-system (in kWp)	4.16	4.16	4.16	4.16
B_{UC} (in kWh)	3.6	3.6	3.6	3.6
E_{PV} (in kWh)	4,100.67	4,100.67	4,100.67	4,100.67
P_{D} (in kWh)	3,534.86	3,534.86	5,644.21	5,644.21
P_{GE} (in kWh)	1,952.74	1,436.23	1,458.52	847.61
P_{GI} (in kWh)	-1,383.33	-866.82	-2,998.46	-2,387.55
E_{DMD} (in kWh)	975.31	1,499.79	1,511.43	1,935.50
E_{BMD} (in kWh)	1,176.22	1,168.25	1,134.31	1,321.16
E_{CT} (in kWh)	2,151.53	2,668.04	2,645.74	3,256.66
c (in %)	0.52	0.65	0.65	0.79
s (in %)	0.61	0.75	0.47	0.58
CS (complete cycles)	326.73	324.51	315.09	366.99
LE (in years)	24.49	24.65	25.39	21.80

4.2 Application and Different Scenarios

A detailed analysis of the aggregated data gives more insight about the results. Where will the produced energy be used? And how is the percental share of each segment?

4.2.1 Base Scenario

Figure 15 shows, that the produced energy will be either directly used (DMD), charged in the battery (BMD) or fed into the grid (grid export).

Category 1

In this base scenario, the first comparison of DINCI and P HH (with equal B_{UC}, E_{PV} and P_D) shows that P HH has 13% higher c (52 compared to 65%) and 14% higher s (61 compared to 75%) than DINCI HH. Additionally, it is important to mention that the BMD has in both HHs almost the same amount of kWh, even slightly higher in DINCI HH (1,176.22 compared to 1,168.25kWh). So, the overall increase of 516.51kWh in E_{CT} (and therefore in c and s) of P HH is solely owned to the DMD (975.31 to 1,499.79kWh). P HH has still no optimum in c (and an overly high s), which might already indicate, that the PV-system is oversized (and therefore economically not optimised) for this household.

This first analysis indicates already the importance of the behaviour and availability of the persons in the household. P HH, which family members are more at home during the day and use various electrical appliances (for cooking – *cooker, extractor fan, etc.*, leisure time – *computer, TV, etc.*, household tasks – *cleaning, washing, drying, etc.*), have a significant higher degree of c and s. Hence, these key factors are significantly depending on the availability of the persons in the household during the day (= time of energy production) as well on their behaviour, i.e. using energy demanding appliances while energy production, less usage during time of no production. The LE of both batteries is over the given LE of >20 years of the data sheet (DINCI 24.49 and P HH 24.65 years).

Category 2

Quite the same picture can be seen in category 2. FNSKPL HH, the family with no school-kids and one parent on parental leave, has 14% higher c (65 compared to 79%) and 11% higher s (47 compared to 58%) than FSKNPL. The E_{CT} of FNSKPL is 610.92kWh higher than of FSKNPL, again, mainly driven by DMD with 424.07kWh. The FNSKPL HH has almost optimum values of c and s in the base scenario, which indicates that this configuration of PV-BESS fits already well to the energy demand, availability and behaviour of the persons in the household. The LE of FSKNPL lies with 25.39 years almost at the same level as in category 1, whereas FNSKPL with 21.80 years is slightly closer to the stated LE of the data sheet (> 20 years), but still within the limits.

Comparing the both categories with each other, it is noticeable, that P HH and FSKNPL (with the same B_{UC} and E_{PV} and a difference in P_D of 2,109.35kWh) have almost an identical allocation of the produced energy (BMD, DMD and P_{GE}). Hence, the difference in P_D must solely be imported from the grid for the FSKNPL HH. That leads to the conclusion, that not the number of persons in the household (2 persons in P HH compared to 4 in FSKNPL) are crucial but much more the fact of being at home of the people and their behaviour dealing with eletronical appliances during the day (except the in generell overall higher energy demand of families with more members). Figure 16 gives an insight about the allocation of the produced energy of all HHs (in the base scenario). It shows again, that in the base scenario just the FNSKPL HH is close to an optimum value in c with 79.35%.

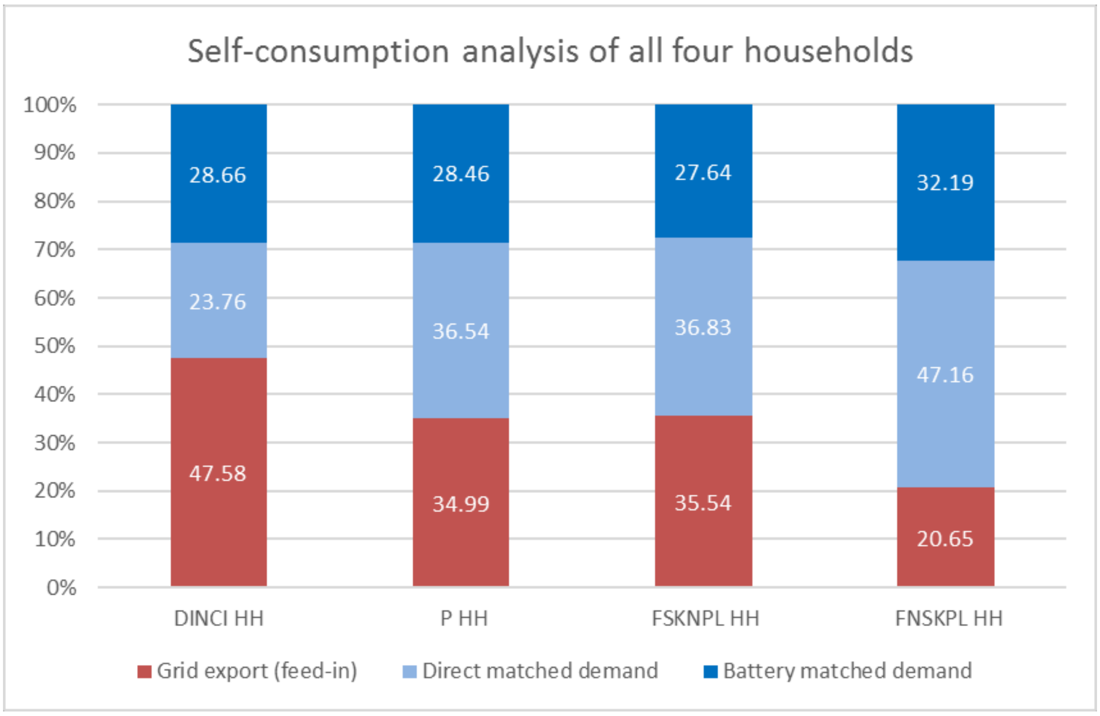

Figure 15: Self-Consumption Analysis of all Four Households - where will the produced energy be used? (own illustration)

What will be the results in performance and self-consumption, when keeping some variables constant, while changing others? In the next paragraphs the outcome of certain scenarios will be shown in more detail.

4.2.1 Scenario 1

How does the size of the PV-system influence self-consumption as well as self-sufficiency of each of the four households?

In Figure 16 and Figure 17 this variation has been illustrated for each of the categories. The variables, yearly total energy demand and capacity of the battery, have been hold constant, while changing the size of the PV-system.

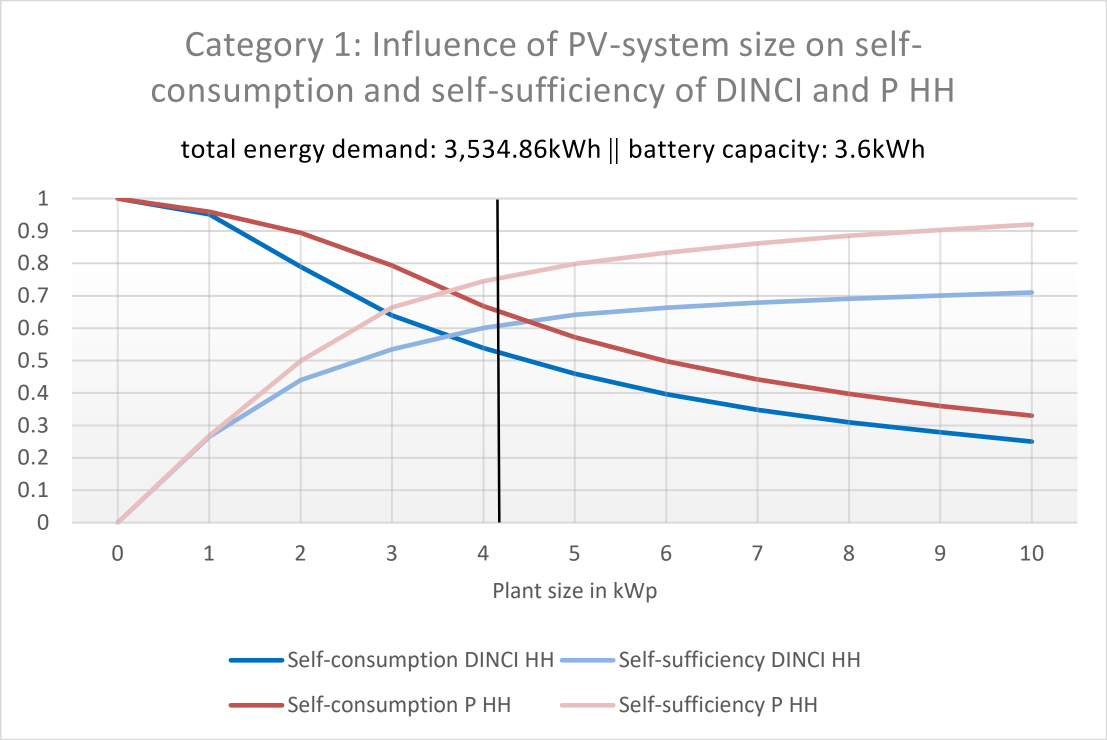

Figure 16: Influence of PV-System Size on c and s of DINCI and P HH (own illustration)

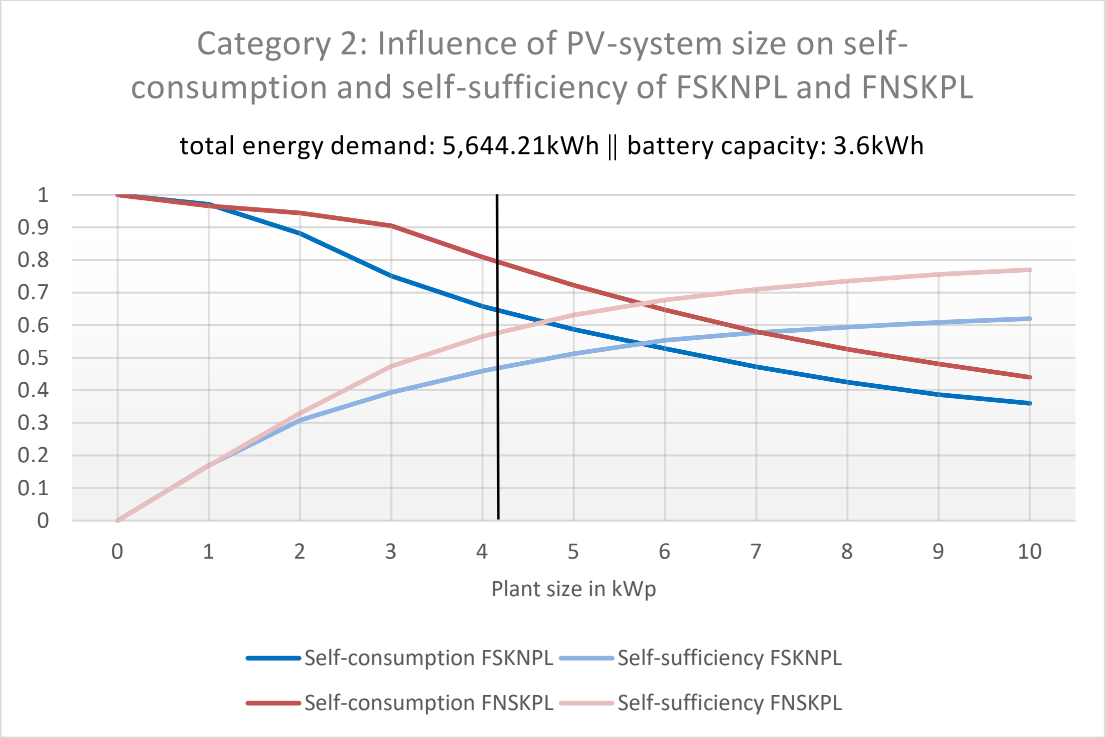

Figure 17: Influence of PV-System Size on c and s of FSKNPL and FNSKPL HH (own illustration)

In order to increase the overall benefit of self-consumption and self-sufficiency and eventually come as close as possible to the set optimum of both key figures, the maximum values (of c + s) along the curve will be calculated. In all underlying cases this leads to a smaller PV-system, which is again beneficial for the households because of minor initial investment costs. On the other hand, this also implicates, that the electricity production is comparatively smaller to the overall demand and so more electricity must be imported.

Category 1

In DINCI HH the size of the PV-system should be decreased to 1.56kWp (6 modules). The resulting degree for self-consumption increased from 52 to 88% and self-sufficiency decreased from 61 to 38%. Even though, the overall percentage of c and s increased by 13%. The relatively small size of the PV-system lead to reduction of complete cycles of the battery and therefore a prolonging LE of 40.72 years. The reduction of the PV-system leads to an optimum in self-consumption, but strongly decreases the self-sufficiency, which is not desirable. In this case, a second battery pack (additional 3.6kWh) might support the overall system effectively.

In P HH the size of the PV-system should be decreased to 2.6kWp (10 modules). The resulting degree for self-consumption increased from 65 to 85% and self-sufficiency decreased from 75 to 61%. The overall percentage of c and s increased by 6%. This configuration of PV-BESS lead to an optimum of both key figures (c and s) in this household. Furthermore, decreasing the size of the PV-system reduces the initial investment costs and even expands the LE to 28.30 years. Targeting the technical and economical optimum (see chapter 2.4. for more details), it is expected that this might be already the best configuration of PV-BESS for this household.

Category 2

In FNSKPL HH the size of the PV-system should be decreased to 1.82kWp (7 modules). The resulting degree for self-consumption increased from 65 to 91% and self-sufficiency decreased from 47 to 29%. The overall percentage of c and s increased by 8%. Similar to DINCI HH, the relatively small size of the PV-system lead to reduction of complete cycles of the battery and therefore a prolonging LE of 44.58 years. Again, the reduction of the PV-system in this HH leads to a strong decrease of s, which is contraproductive for the overall system performance.

In FSKNPL HH the size of the PV-system should be decreased to 3.12kWp (12 modules). The resulting degree for self-consumption increased from 79 to 89% and self-sufficiency decreased from 58 to 49%. The overall percentage percentage of c and s increased by 1%. In this case, the overall change is very marginal, actually from 3.12 to 4.16kWp the change is within 1% and it just changes the percentages between c and s. Beneficial for this HH is that the smaller PV-system reduces the costs of initial investment, but for the sake of 9% of s. Therefore, it highly depends in this HH on local costs of initial investment, price of retail kWp for the consumer, etc., in order to make a decision if this change of configuration of the PV-BESS makes technically and economically sense or not.

Overall it can be said, that the shrinking of the PV-system boosts the self-consumption, but for the most part at the costs of self-sufficiency. This configuration of PV-BESS (keeping behaviour, B_{UC} and P_D constant) supports the overall increase in c and s and reduces the initial investment costs for each HH. But the decline in s (DINCI 38%, FSKNPL 29% and FNSKPL 49%) lead to an unwanted increase of P_{GI}. Just in the case of P HH this configuration brings an overall benefit for the HH.

Table 5: Summary of Key Figures of each Household (Scenario 1) (own illustration)

	Category 1		Category 2	
	DINCI HH	P HH	FSKNPL HH	FNSKPL HH
PV-system (in kWp)	1.56	2.6	1.82	3.12
B_{UC} (in kWh)	3.6	3.6	3.6	3.6
E_{PV} (in kWh)	1,541.35	2,566.52	1,797.64	3,079.10
P_D (in kWh)	3,534.86	3,534.86	5,644.21	5,644.21
P_{GE} (in kWh)	188.76	393.48	168.32	327.38
P_{GI} (in kWh)	-2,182.27	-1,361.82	-4,014.89	-2,892.49
E_{DMD} (in kWh)	645.34	1,155.47	983.30	1,607.08
E_{BMD} (in kWh)	707.25	1,017.57	646.02	1,144.64
E_{CT} (in kWh)	1,352.59	2,173.04	1,629.32	2,751.72

c (in %)	0.88	0.85	0.91	0.89
s (in %)	0.38	0.61	0.29	0.49
∑ of c + s (in %)	+13	+6	+8	+1
CS (complete cycles)	196.46	282.66	179.45	317.96
LE (in years)	40.72	28.30	44.58	25.16

4.2.2 Scenario 2

How does the size of the battery capacity influence self-consumption as well as self-sufficiency of each of the four households?

In Figure 18 and Figure 19 this variation has been illustrated for each of the categories. The variables, yearly total energy demand and size of the PV-system, have been hold constant, while changing the capacity of the battery.

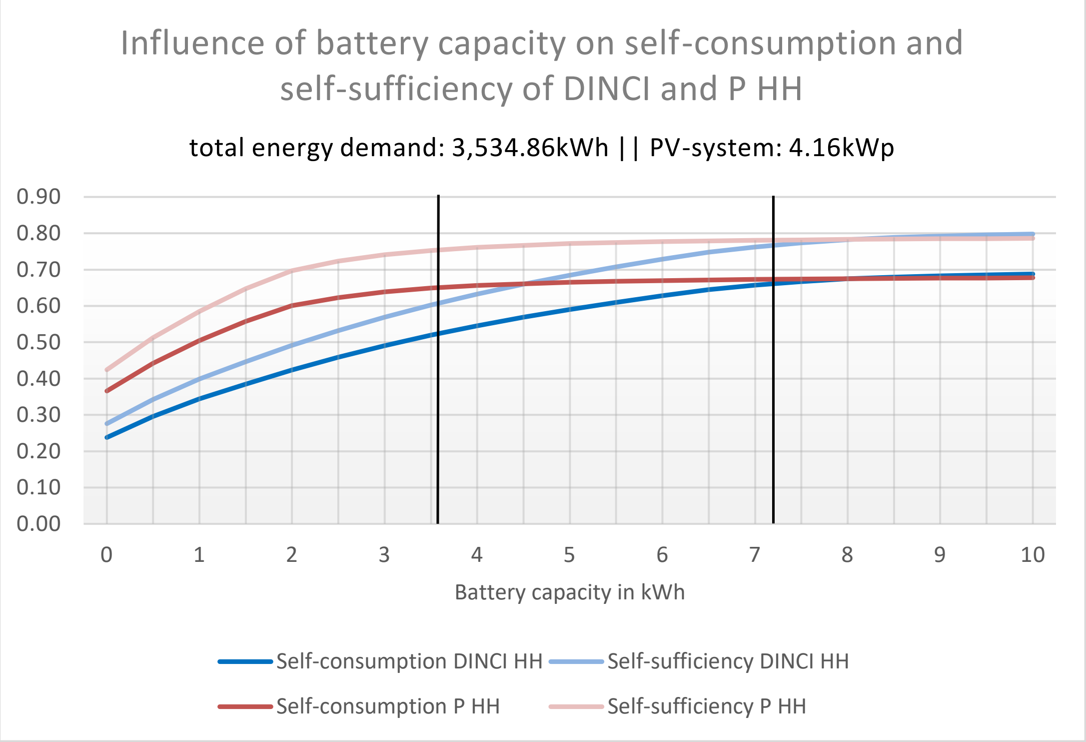

Figure 18: Influence of Battery Capacity on c and s of DINCI and P HH (own illustration)

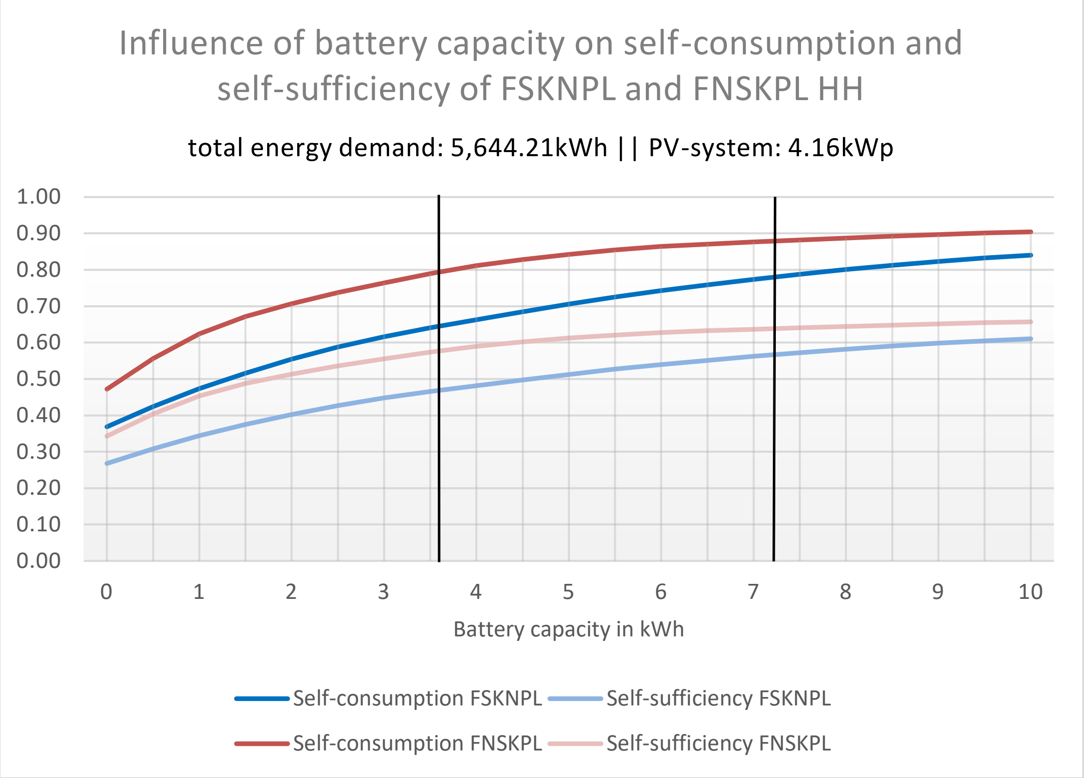

Figure 19: Influence of Battery Capacity on c and s of FSKNPL and FNSKPL (own illustration)

In order to be able to compare all values properly a second battery pack (3.6kWh) from Fronius has been added to the systems, so the capacity of the batteries goes up to a maximum of 7.2kWh. In Figure 18 can be seen, that P HH is already almost at the maximum of c and s and a further increase of battery capacity (black vertical lines in the diagrams indicate both battery packs) won't have a substantial impact in this household anymore. For the other families, a second battery with 3.6kWh will support the system in a positive way, keeping in mind the additional costs of this second battery pack. The results of the self-consumption analysis are shown in the following Figure 20.

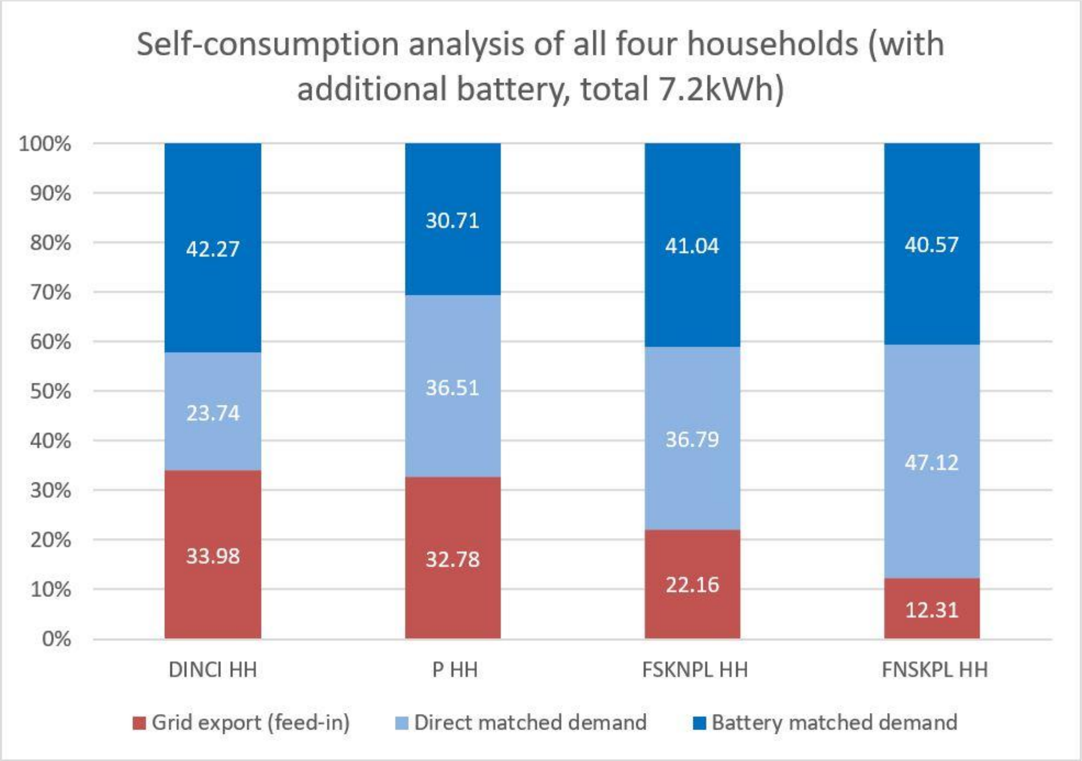

Figure 20: Self-Consumption Analysis of all Four Households (with additional Battery 3.6kWh, total 7.2kWh) (own illustration)

A first analysis of Figure 20 as well as the dataset with the second battery shows already, that the higher battery capacity strongly supports the DINCI and FSKNPL households (DINCI: BMD increases by 560.30kWh; FSKNPL: BMD increases by 551.63kWh), whose family members are not as often at home and don't directly consume the produced energy as much as the other households in the same category. The E_{DMD} does not change, just the E_{BMD} and therefore also the E_{CT}.

Category 1

In DINCI HH the doubled battery capacity of 7.2kWh (2 x 3.6kWh) increases the overall degree of self-consumption from 52 to 66%, which is still no optimum for this HH and implies that as additional step a reduction of the PV-systems might help. The degree of self-sufficiency climbs from 61 to 77%, which clearly shows the positive influence of an additional battery pack within this family and set of behaviours. It supports this family with its set of behaviours (not so much at home while time of highest electricity production) very effectively. The overall percentage of c and s boosts by 30% and also LE raises, due to the better distribution of the stored energy between the two battery packs, up to 33.17 years.

In P HH a doubled battery capacity of 7.2kWh (2 x 3.6kWh) just slightly increases the overall degree of self-consumption from 65 to 67%. Also, the degree of self-sufficiency gains just a minor rise from 75 to 78%. The overall percentage percentage of c and s slightly increases by 5%. Again, due to the better distribution of the stored energy between the two battery packs LE rises up to 45.66 years.

In scenario 1, P HH has 18% more c (85%) but 17% less s (61%). The important difference is, that in scenario 1 P HH can lower its initial investment (smaller PV-system by 6 modules), whereas in scenario 2 a second, costly battery pack must be installed. So, the favourised configuration for P HH is still scenario 1. For this family and its pattern of behaviour a second battery pack does not pay off.

Category 2

In FNSKPL HH the doubled battery capacity of 7.2kWh (2 x 3.6kWh) has again a strong impact on the degree of self-consumption from 65 to 78% as well as on the degree of self-sufficiency from 47 to 57%. LE rises up to 34.16 years. These numbers are already close to the projected optimum of c and s, which shows the importance of an additional battery pack within this family and set of behaviours (not so much at home while time of highest electricity production). The overall percentage of c and s strongly increases by 23%. This might be already the best configuration of this household with its set of behaviours, because any increase of the size of the PV-system will lead to an increase of c as well as decrease of s, and vice verca.

In the case of FSKNPL HH, the doubled battery capacity of 7.2kWh (2 x 3.6kWh) rises self-consumption from 79 to an optimum degree of 88%. Also, the degree of self-sufficiency ascents from 58 to 64%. LE increases up to 34.56 years. Despite its previous already almost optimum c (79%), a second battery pack robustly supports this family, including its pattern of behaviour (high demand during the day). Compared to P HH, which has a similar set of behaviours, the higher total electricity demand of FSKNPL (3,534.86 compared to 5,644.21kWh) effectively uses the second battery pack. For this family and its pattern of behaviour a second battery pack helps the PV-BESS. The overall percentage of c and s effectively increases by 15%.

Overall it can be said in scenario 2, that a second battery pack (additional 3.6kWh) supports the behaviour of not being often at home during the time of electricity production in order to use the produced and stored energy from the battery later on. Additionally, a larger battery capacity helps the load curve of families, who have more members and spend more time at home (like FNSKPL HH), because this structure also tends to have a higher total energy demand. Last but not least, a second battery reduces the complete cycles of each battery and therefore expands LE of the batteries.

Table 6: Summary of Key Figures of each Household (Scenario 2) (own illustration)

	Category 1		Category 2	
	DINCI HH	P HH	FSKNPL HH	FNSKPL HH
PV-system (in kWp)	4.16	4.16	4.16	4.16
B_{UC} (in kWh)	7.2	7.2	7.2	7.2
E_{PV} (in kWh)	4,100.67	4,100.67	4,100.67	4,100.67
P_{D} (in kWh)	3,534.86	3,534.86	5,644.21	5,644.21
P_{GE} (in kWh)	1,396.04	1,346.62	910.50	505.77
P_{GI} (in kWh)	-823.03	-773.61	-2,446.84	-2,042.11
E_{DMD} (in kWh)	975.31	1,499.79	1,511.43	1,935.50
E_{BMD} (in kWh)	1,736.52	1,261.46	1,685.94	1,666.60
E_{CT} (in kWh)	2,711.83	2,761.25	3,197.37	3,602.10
c (in %)	0.66	0.67	0.78	0.88
s (in %)	0.77	0.78	0.57	0.64
∑ of c + s (in %)	+30	+5	+23	+15
CS (complete cycles)	241.18	175.20	234.16	231.47
LE (in years)	33.17	45.66	34.16	34.56

In a last step, it is interesting to see, what final configuration of PV-BESS comes closest to the targeted key figures of 80% c and 60% s of each household.

Chapter 5: Conclusion & Outlook

In the last chapter, various effects and dependencies of the given households with its pattern of behaviours and different configurations of the PV-BESS could be shown and explained in the four different case studies. In the following a best possible PV-BESS will be chosen for each HH (in order to come as close or even above the target values of c and s) and eventually a critical discussion about the underlying data, case studies and calculations will be held.

Conclusion of the aggregated and calculated data

The following conclusions are just valid under the already mentioned *additional assumptions* from chapter 2.4.

Category 1

DINCI HH

A PV-system with 4.16kWp is to large for a household with two fully employed residents and no kids. In the base scenario, the DMD is just 975.31kWh compared to 1,499.79kWh of P HH. The reduction of the PV-system (to 1.56kWp) in scenario 1 boosts the self-consumption up to 88%, but at costs of self-sufficiency, which drops to 38%. So, the household still needs to purchase 62% of all kWh from the energy utility, which is not desirable. As a consequence, the implementation of a second battery pack (additional 3.6kWh) is supportive and recommended.

The final configuration of the PV-BESS for the DINCI HH is a 2.6kWp PV-system including a second battery pack (total 2 x 3.6kWh). Hence, the initial investment will be higher (additional battery pack minus smaller PV-system), but c increases to an optimum of 85% (increase of 33% from the base scenario) and s to an optimum of 62% (increase of 1% from the base scenario). Due to the double battery system, also the LE increases to 41.76 years.

P HH

The pensioner's household has a completely different set of behaviours, because the two pensioners stay often at home and use electrical appliances during the time of PV electricity production. This leads already at the base scenario to a good self-comsumption of 65% and an optimum self-sufficiency of 75%. The red curves of Figure 19 show, that in the given situation of P HH (PV-system with 4.16kWp and 3,534.86kWh total energy demand) c and s are already almost at the peak with one battery pack of 3.6kWh. Following the two red lines, it would even be possible, to slightly reduce the size of the first battery pack without major reductions of c and s. In order to utilise more of the produced energy, save initial costs and come closer to the targeted values of c and s in P HH, it is favourable to decrease the size of the PV-system. So, it has been adjusted to 2.6kWp, which leads to an optimum of c of 85% and an optimum of s of 61%. The smaller size of the PV-system also increases LE of the single battery to 28.30 years.

Further interesting finding: The values of c and s in the base scenario of P HH are almost similar to DINCI HH including an additional battery pack (3.6kWh). That means, similar households (DINCI and P HH: two family members with equal E_{PV} and P_D) have almost similar c (66 and 65%) and s (77 and 75%), despite the fact, that DINCI needs an additional battery pack (3.6kWh) in order to reach these values of c and s. In other words, due to the favourable behaviour of P HH (time of using electrical appliances in the HH often overlaps with time of energy production, etc.), this HH can save expenses of a second battery pack of 3.6kWh.

FSKNPL HH

Even though this family has a similar set of behaviours like DINCI, their overall demand in energy is higher because of more family members (3,534.86 compared to 5,644.21kWh). So, this household has just 65% in c and 47% in s in the base scenario. Following the idea, that a larger battery capacity supports families, who are not often at home and/or use their electrical appliances increasingly outside of the energy production during the day, the installation of an additional battery pack (3.6kWh) boosts these values already to almost optimum of 78% in c, respectively 57% in s.

In this case, it is interesting that a reduction of the PV size does not add value to the target values of c and s. A change of the size of the PV-system between 2.86kWp (11 moduels) and 4.42kWp (17 modules) just shifts the maximum values of c to s, and vice versa. In further analysis, it would be necessary to compare the savings out of the own produced kWh to the costs per kWh from the grid import and the investment costs of the PV-system. Obviously, the investor has less investment costs with a smaller PV-system, but also the amount of self-produced kWh is lower and therefore the savings, which arise through the difference between kWh produced and kWh grid import.

As a consequence, in the given situation of FSKNPL HH it is not possible to reach an optimum for both key figures of c and s. The final configuration of PV-BESS of 4.16kWp and 7.2kWh battery size just lead to almost optimum values of c of 78% and s of 57%. The second battery pack supports the whole system and expands LE to 34.16 years.

FNSKPL HH

This family with four members is often at home and has a high demand of energy. So, already the base scenario leads to a very good c of 79%, respectively s of 58%. This indicates already that the PV-system has the adequate size for the total energy demand and set of behaviours. A reduction in PV size does not positively influence the target values.

Again, the values of c and s in the base scenario of FNSKPL HH are almost similar to FSKNPL HH including an additional battery pack (3.6kWh). That means, similar households (FSKNPL and FNSKPL HH: four family members with equal E_{PV} and P_D) have almost similar c (78 and 79%) and s (57 and 58%), despite the fact, that FSKNPL needs an additional battery pack (3.6kWh) in order to reach these values of c and s. In other words, due to the favourable behaviour of FNSKPL HH (time of using electrical appliances in the HH often overlaps with time of energy production, etc.), also this HH can save expenses of a second battery pack of 3.6kWh.

Adding a second battery pack (additional 3.6kWh) to FNSKPL HH inceases the values of c to 88% (+9%) and s to 64% (+6%). The additional capacity supports the PV-BESS due to its high DMD and total energy demand. If the investment of a second battery pack is economically feasible depends much on the local initial investment costs of the battery pack, price of retail kWp for the consumer (increase of E_{CT} from 3,256.66 to 3,602.10kWh), etc.,

In the following Table 7: Summary of Best PV-BESS to Increase c and s of each Household (own illustration)7 the “best” solutions for each household of the PV-BESS in order to reach the target values of c (80%) and s (60%) have been summarized.

Table 7: Summary of Best PV-BESS to Increase c and s of each Household (own illustration)

	Category 1		**Category 2**	
	DINCI HH	**P HH**	**FSKNPL HH**	**FNSKPL HH**
PV-system (in kWp)	2.6	2.6	4.16	4.16
B_{UC} (in kWh)	7.2	3.6	7.2	7.2
E_{PV} (in kWh)	2,562.92	2,566.52	4,100.67	4,100.67
P_{D} (in kWh)	3,534.86	3,534.86	5,644.21	5,644.21
P_{GE} (in kWh)	388.69	393.48	910.50	505.77
P_{GI} (in kWh)	-1,353.43	-1,361.82	-2,446.84	-2,042.11
E_{DMD} (in kWh)	801.98	1,155.47	1,511.43	1,935.50
E_{BMD} (in kWh)	1,379.45	1,017.57	1,685.94	1,666.60
E_{CT} (in kWh)	2,181.43	2,173.04	3,197.37	3,602.10
c (in %)	0.85	0.85	0.78	0.88
s (in %)	0.62	0.61	0.57	0.64
∑ of c + s (in %)	+34	+6	+23	+15
CS (complete cycles)	191.59	282.66	234.16	231.47
LE (in years)	41.76	28.30	34.16	34.56

What is the final answer to the research question?

The initial data acquisition and information research is the most important part while configuring a PV-BESS. Obviously, the first task is to evaluate the possibilities of a PV installation, like size of rooftop, inclination, angle, estimated energy production, acquisition costs, etc. Due to shrinking incentive prices, the size of the PV installation is in most cases not the hindrance anymore. Nowadays, maximising the overall energy self-consumption (E_{CT}) of a system is in most residential and commercial cases economically favourable. But at this point a final decision making is already vastly depending on local pricing, costs, charges, regulations and tariff structures. Is there an incentive system for PV/batteries in place (one time or feed-in)? Is the incentive/selling price to the utility company (fixed for 13 years) higher or lower as the electricity retail price of the end consumer? What might be the rise of energy costs during the investment horizon? The answers to these questions will set cetain conditions, where investments in a PV-BESS (and size of PV, battery, etc.) will be feasible/desirable for a houseowner or not. After intense research and compiling and using the calculator in different case scenarios, target values for the key figures of the degree of self-consumption as well as the degree of self-sufficiency have been set in this master thesis. The main objective was to find useful and effective values (c >= 80% and s >= 60%), with the aid of combining results of various studies, which are technically as well as economically true at the time of writing.

Therefore, every PV-BESS of every household has been configured towards a technical and economical optimum of c and s. That implies, that a specified household with a PV-BESS with 80% c and 60% s, is economically feasible and desirable. Therefore, certain conclusions have been drawn out of the calculations (second battery pack does have a positive effect on c and s or not, etc.) and suggestions for improvement have been stated. Cases of close decisions ("Is an increase of 9% c and 6% s (overall increase of E_{CT} is 345.44kWh p.a. worth an investment of an additional battery pack of 3.6kWh in FNSKPL HH?") have been identified and discussed, but deliberately not calculated. Any assumptions of investment costs and/or energy prices would influence the outcome and specify it to the time of this master thesis. Because costs for batteries and PV-systems, electricity retail prices for the end consumer, selling/incentive prices to the local utility company, certain incentive systems in place for PV and/or batteries are varying in time and location rapidly and are even changing while writing this paper. The profitability/feasibility of a PV-BESS and therefore also a high self-consumption and self-sufficiency is strongly depending on technical, economical and even regional political decision making, influencing local prices, regulations and tariff systems. So, a final solution for a economically "optimal" value of self-sufficiency of a PV-BESS cannot be generally given.

Chapter 5:
Conclusion & Outlook

After determining additional assumptions as well as setting target values for c and s (under these assumptions) and inserting all values into a self-compiled calculator, the configuration of a PV-BESS is unproblematic. The size of the PV-system as well as the battery directly influences c and s – increasing the size of PV leads to a higher c and smaller s, and vise verca. Whereas, including an additional battery pack (more capacity) greatly supports households, whos family members are not often at home (= not using electrical appliances during time of energy production), and vica verca. These outcomes might not be totally new, but the comparisions between the households could give an insight of the importance of the actual behaviour of the persons in the HH.

The pattern of behaviour of the residents of a household is strongly influencing the performance of a PV-BESS – every set of behaviours, which increases DMD, leads to a positive influence for the overall performance of the PV-BESS. So, all kind of energy intense behaviours, like cooking, vacuum cleaning, washing, etc. should be carried out during the time of high energy production of the PV-system. This can easily be realized, when the family members are often at home during the day, like in the P and FNSKPL households. Obviously, this does not work with DINCI and FSKNPL households so comfortable.

But in the near future (grid) connected appliances and smart metering devices can help to achieve this. For example, (dish) washing machines can be automatically activated during the time of enough energy production. Also, the level of activation and deactivation of appliances like the fridge or the freezer can be adjusted to a certain degree – e.g. it is possible to refrigerate to a lower temperature (inbetween the possible range) at times of high energy production (excess energy) in order to extent the time of no deep freezing. There are already appliances and management systems in the market, which can even forecast the weather conditions in order to increase the performance of such PV-BES- systems even more.

The severity of the behavourial influence can clearly be seen in each of the two categories. DINCI household needs an additional pack of battery (additional 3.6kWh) just to reach the same degree of self-consumption and self-sufficiency like P HH (with matched kWh of energy production as well as energy demand of both households). The same result can be seen in category 2. Also, FSKNPL HH needs to double the battery capacity (additional 3.6kWh) in order to get to the same level of c and s like FNSKPL. In both cases, the only difference lies in the different set of behaviours of the two, repectively four residents.

Furthermore, the strong influence of behaviour can also be even seen between the two categories. Comparing P and FSKNPL HH with the same PV-BESS in the base scenario, shows that E_{CT} (therefore E_{DMD} and E_{BMD}) has almost the same value, even though the different size of family members. Self-consumption is exactly the same, just the self-sufficiency is different, because of the higher total energy demand of the family with the four members. In other words, the number of family members does not influence a PV-BESS (except a higher overall demand), but the behaviour of each person in the household does.

Critical review of the calculation, conclusion and used dataset

Last but not least, it is necessary to discuss the quality of the used dataset and also the calculations and results of this master thesis.

MBS dataset

The qualitative MBS dataset from R. Sterrer and W. Prüggler has been defined by a project consortium[19], which means that the underlying pattern of behaviour of each household respectively person (cooking behaviour, vacation behaviour, etc.), has been manually put together in the best of knowledge by this consortium. They compiled load profiles of four different Austrian households for an entire year, which set of behaviour is probable, but does not reflect actual recorded sets of data or sets of behaviours of Austrian residents. This must be considered when reading the results of this case study.

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[19] Project consortium was composed of FH Technikum Wien – Institut für Erneuerbare Energie, EVN AG, ATB- Becker, KEBA AG, Cellstrom GmbH und der TU WIEN – Energy Economics Group.

Furthermore, the assumed yearly energy demand of each household is just given in hourly values. This is expected to be the greatest disturbance value in the dataset. Hourly values smoothen out all changes in demand during the whole hour (peaks, oscillation, shifts, etc.). For example, the activation of an electric water kettle causes high energy demand in just seconds or minutes, but in the hourly values it is aggregated with all other energy demands for the whole hour. This implicates, that in a real situation, the energy demand within this hour leads to a strong fluctuation in energy management. Most of the minutes of an hour might be covered from the PV production during the day and even lead to charging of the battery. But at moments of high energy demand (e.g. due to the acitvation of the water kettle) the system needs more energy from the grid or from discharging of the battery. So, there is regular change between charging/discharging/grid import/grid export in the system within this hour. In the MBA dataset, all the values are aggregated to hourly values and just the total energy production as well as total energy demand of this hour are compared at the end. In case of excess energy, the energy surplus will be charged into the battery or exported into the grid and in case of energy deficit the battery will be discharged or energy will be taken from the grid. All fluctuations including energy losses, small charging/discharging movements, reaction times of the battery, etc. are not taken into account in this case study. It would lead in the PV-BESS to less benecial degrees of self-consumption and self-sufficiency. Moreover, the cycle life as well as life expectancy of the battery would negatively be influenced. After compiling the calculator and running through different case scenarios as well as doing a lot of research for this master thesis, the overall impact of this disturbances is expected to be more than 10% of the results. In order to get more realistic values and results, it would be important to get yearly datasets of demands as well as of production in intervals of seconds.

PVGIS dataset

Probably the second biggest disturbance value in this case study is the fact, that all irradiation values of PVGIS are averaged values. For example, the data contains average values (W/m^2) for every hour in January between 1998 till 2011. As a consequence, every day in January has the same amount of irradiation. In the database are no cases of (many consecutive) foggy, rainy or cloudy days. This leads to a balanced PV production within the same month, which is not a realistic scenario. The realistic bottleneck of a PV-BESS will increasingly appear during a longer period of bad weather without any sunlight. These will be the times of very high grid import, because of no PV production and an empty battery system. This is also why the final percents of full self-sufficiency are almost impossible to gurantee and the PV-BESS would have to become prohibitively large.

The overall averaged values per year in kWh might be very close to the real outcome (including losses due to temperature, low irradiance, cables, inverter, etc.) of a PV system, but the closer the look to a certain time, the bigger the spread. This issue also leads to a less favourable outcome in performance of the PV-BESS (higher grid import, higher grid export and less battery usage). The overall impact of this disturbance is expected to be again up to 10% of the results. In order to reduce this issue, it would be necessary to record the actual irradiation data of a certain location of a complete year.

Inertial of BMS

The inertial of the battery adjustment is another issue, which need to be considered when a dataset is more precise. The small shifts during energy surplus and deficit would need a very quick reaction time from the battery management system. But normally the import/export of the grid reacts much faster than the charging/discharging of the battery. That leads again to a negative impact on the degree of self-comsumption and self-sufficiency. In reality the control system of the battery can be very slow and inaccurate. A PV-BESS, which completely works without grid connection, must be massively oversized, in order to compensate demand peaks (like a water kettle, electric cooking oven, etc.) as well as gaps in energy production whle periods weeks and months of no or little sunlight. But the inertial of the battery management system does not have as strong impact as the other two mentioned factors above. This and other negligible disturbances like additional battery losses haven’t been considered in this master thesis.

Data sheets of the companies

The mentioned disturbances and deficiancies of the established calculator as well as the assumptions, which needed to be set in place for this case studies, lead to deviations of the resulting values. In the data sheet of the battery pack from Fronius, it is stated, that LE of the battery pack is >20 years. In all calculations and results of the configured PV-BESS of each household this maximum LE (cycle life) could even be topped. In the specs sheet it is further stated that this maximum cycle stability of 8,000 cylces and therefore a cycle life of >20 years can just be reached at 23° ambient temperature. A cycle stability of 8,000 cycles in a field test is more than unlikely and should be analysed in a further research. Comparable studies and various literature, not company's own spec sheets, are stating currently 1,000 to maximum 5,000 complete cycles for Li- ion- batteries, which would result in about half of the calculated LE (ISEA, 2016) (T. Dragicevic, et al., 2014). Furthermore, due to the already mentioned additional losses and the estimated depth of discharge (again highly depending on the battery, BMS, temperature and storage conditions) the maximum LE of the batteries of the HHs would be probably even <10 years in actual field tests.

In this case study, the impacts and consequences of four different households (with certain sets of behaviour) to the PV-BES- system have been compared with each other. It is necessary to be aware of all mentioned inaccuracies of the datasets. Nevertheless, the compared values (often differences) of the households have the same level of disturbance/inaccuracy at the moment of its comparison. So, the final results of the comparisons might not be as strongly influenced as expected.

Concluding this master thesis, a possible outlook for PV-BESS will be given. Following a further decrease of costs of PV-systems and even more of home battery packs, an ongoing increase of PV-BESS is to be expected. At the moment, a positive market penetration is highly depending on costs of hardware and installation, local energy prices, tariff systems in place and so on. But it has also been shown in this paper, that it is predicted, that kWh prices of renewable energy carriers as well as battery packs will internationally keep on declining (and most probably retail energy kWh costs keep on increasing), which will eventually make investments in PV-BESS more and more feasible, similar to the worldwide development of PV, independent of local structures.

At the moment, this paper could demonstrate, that adequate behaviour (adjusted towards high DMD) could cut investment costs of a PV-BESS (c>= 80% and s>= 60%) by an additional battery pack of around 3.6kWh. This is even true for households with two residents as well as four residents (and a different in total energy demand of 3,534.86 and 5,644.21kWh). As a consequence, an adjusted behaviour of the persons in a residential household make a significant financial difference (of about a 3.6kWh battery pack; within the stated assumptions).

Furthermore, various ongoing and upcoming developments, like demand side management including demand response (adjusts demand for energy rather than supply), central storage (e.g. multi-family house, apartment building, etc.) and virtual storage power plans (cross-connection of battery units divided by local area) as well as load-variable tariffs, smart meters and grids in order to fulfil certain tasks – decoupling of supply and demand; energy buffer for peak currents; etc. – will diminish this impact of behaviour of the residents. Most of the energy demand intense applications of the members of the HH will be automatically activated during times of high energy supply or spread over wider areas in order to balance the demand/supply. Due to limitations of scope in this master thesis, these developments will not be further analysed and give opportunity for further research in this topic.

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Appendix A: Description of Load Profiles

Name	Consumption Type	Unit	Power [W]	Stand-by [W]	Energy per use [Wh] / duty cycle [min]
Electric cooker	NAV KZV	Siemens HV330510	10480	5	30min
Extractor fan	NAV KZV	Neff I72F57N0	295	1	30min
Washing machine	NAV KZV	Siemens WM16S843		2	1030Wh
Clothes dryer	NAV KZV	Siemens WT46W560		2	1160Wh
Dishwasher	NAV KZV	Neff SS2M53X1EU		2	970Wh
Vacuum cleaner	KZV	Bosch BSG81466	1400	0	25min
Refrigerator	NUV	Siemens KI28FP70	120	1	197,47kWh/a
Freezer	NUV	Siemens GF18DA50	90	1	193.82kWh/a
Computer	NAV	Desktop	200	0.2	
TV	NAV	Sony KDL-40HX800	88	0.2	
Toaster	KZV	Bomann TA 1962 CB	826		3min
Water cooker	KZV	Unold 18566 Blitzkocher Pisa	1800		3.5min
Coffee machine	KZV	Severin KA 4031	1000		6min
Stereo system	NAV	Marantz AV Receiver	65	2	
Simple radio	NAV	HERU Kitchen Radio	3		
Hair dryer	NAV	Philips HP8182/00	2200		4,5min
Gas, oil, pellet heating	NUV	Pellets IDRO 314	120	2	
Microwave	NAV KZV	AEG KM9800E	1000	1	3.5min
DVD player	NAV	YAMAHA DVD-S2700	30	0.2	
Powerful tools (drilling machine, circular saw, high pressure steam cleaner, wood splitter, ..)	NAV KZV	Bosch PHB 2800 RE	750		15min
Circular saw	NAV	Metabo BKS 400 Plus	3100		
High pressure steam cleaner	NAV KZV	CSC 5375	1100		15min

Ventilation restroom, bath	NAV	Siku-fan		14	
Controlled residential ventilation	NUV	HomeVent RS-250	150	2	400kWh/a
Mixer	KZV	AEG M 2600	600		2min
		light on when	power is not opt.		
Light living room	LV	twilight	300W		
Light bedroom	LV	darkness	100W		
Licht cellar	LV	always	50W (neon tube)		
Light outdoor	LV	darkness	100W		
Light kitchen	LV	dismal weather	150W		
Light storage room	LV KZV		60W		15
Light garage	LV KZV		50W (neon tube)		10
Light workshop / hobby room	LV	always	50W (neon tube)		
Light children's room	LV	dismal weather	100W		
Light restroom	LV KZV		60W		5
Entrance hall / staircase	LV KZV		200W		20
Light bathroom	LV	dismal weather	100W		

Remarks:

- All assumptions are yellow
- For all four households, the relevant climate data (duration of lights, etc.) of Wiener Neustadt has been used.

DINCI HH ... Double income no kids

♣ Two professional adults

♣ Working hours 08:00 - 17:00

♣ During the week usually only one in the evening at home on two days both

♣ Weekend behavior often not at home (assumption about 40% of the weekend no one at home)

♣ Cleaner ... Cleaning, washing and ironing once a week during the day

♣ Vacation 5 weeks a year always not at home. Summer 3 weeks, winter 2 weeks

♣ **Cooking behavior:**

♣ Dinner during the week yes, on weekends only when at home

♣ Lunch at the weekend 50% of the time when the family is not on the road - remaining time the family goes out for a meal

♣ Breakfast during the week yes, on weekends only when at home

♣ **Leisure activities when at home:**

♣ Television x hours a week

♣ Computer x hours a week

IMPLEMENTATION

- Holiday: summer: 09.08.-28.08. winter: 13.02.-26.02.
    - all appliances are off, except: refrigerator, freezer, pellet heating
- Breakfast: weekdays: 07: 00 weekends: 09: 00
    - radio 2h, toaster 2x, water boiler 1x, coffee machine 1x, light kitchen 1h
- Weekends: departure FR afternoon, arrival SUN afternoon
    - on the road: see calendar
- Cleaning MO 9: 00-14: 00: washing machine 3x, dryer 3x, vacuum cleaner 3x, lights 3h or 3-5x, (water cooker 1x, microwave 1x)
    - + 1x washing + drying THU 19:00
- Dinner 18:00:
    - stove 1x (20min, half power due to GLZ, + extractor hood), light kitchen 2h, dishwasher MO, WED, FR
    - if both at home (TUE & THU): microwave 1x, mixer 1x, water cooker 1x
    - weekends 19:00: microwave 2x, water cooker 1x

- Leisure activities:
  - television daily 20:00-22:00 excl. SAT, always over stereo system, MO & THU DVD
  - stereo system, additionally 12h/week
  - computer: 14h/week (especially weekends)
- Working hours 08:00 - 17:00:
  - mornings from 6h: hairdryer 1x, ventilation bath-restroom 1h, light restroom 2x, light bedroom 1h, light bath 1h, light garage 2x
  - evenings: light garage 3x, light bedroom 21:00-23:00, light living room 18:00-22:00, light storage room 2x, light restroom 6x, light entrance hall 2-3x, light bathroom 1h, ventilation bath-restroom 1h, light outdoor 1h
- Weekends:
  - mornings from 9h
  - 50% cooking at noon 13:00: stove + extractor x2, water boiler 1x, mixer 1x
- Others:
  - light workroom MI 2h, light cellar 3h/week
  - no light children's room
  - drilling machine 5x15min./a, high pressure steam cleaner spring + autumn 3h (27.3 + 23.10.), circular saw 2x6h/a (15th + 16th October)
  - pellet heating winter 6h/d (Oct.-March), summer 3h/week (Apr.-Sept.)

P HH ... Pensioners' household

- ♣ Two adults in pension
- ♣ Under the week 100% both in the evening at home
- ♣ Weekends 70% at home, 30% weekend trips throughout the weekend
- ♣ Cleaning: cleaning, washing and ironing once a week during the day
- ♣ Holiday 5 weeks a year, summer 2 weeks, winter 3 weeks
- ♣ **Cooking behavior:**
- ♣ Dinner during the week 100%, on weekends 100%
- ♣ Lunch during the week 100%, on weekends 50%
- ♣ Breakfast during the week 100%, on weekends 90%
- ♣ **Leisure activities when at home:**
- ♣ Television x hours a week
- ♣ Computer x hours a week

IMPLEMENTATION

- Holiday winter 06.02.-22.02. summer 03.06.-17.06. & 30.10.-06.11.
  - all devices of excl. refrigerator, freezer, pellet heating
  - weekends see calendar (30% corresponds to 13 weekends): as vacation but controlled residential ventilation on, departure FR afternoon, arrival SUN afternoon
- Daily routine:
  - mornings from 6:00: light bedroom 1h, light bathroom 2h, hairdryer 1x, ventilation toilet, bath 1h
  - breakfast 7:00: coffee machine 1x, water cooker 1x, toaster 2x
  - cooking from 11:00: stove & extractor hood 2x (20min, half power due to GLZ), mixer 1x, water cooker 1x
    - weekends (50%): additionally: stove & extractor hood 1x, mixer 1x, water cooker 1x
  - dinner 18:00: microwave 2x, water cooker 1x
  - sleeping 20:00, SAT 22:00: light bedroom 2h, light bathroom 1h
- Leisure activities:
  - television daily 16:00-20:00 (SAT until 22:00), additionally 9h/week distributed throughout the day, DVD 2x/week
  - radio 6:00-16:00, stereo system 15h/week

  - afternoon coffee 15:00: coffee machine 1x, toaster 1x
- General:
  - light kitchen 06:00-19:00, light living room 07:00-20:00
  - light hobby room 15h/week, light cellar 3h/week, light storage room 10x/week, light outdoor 15h/week, light garage 16x/week
  - light restroom approx. 15x/d, light entrance hall 2-4x/d
  - dishwasher SUN, WED, FR 15:00
  - cleaning TUE morning & afternoon: washing machine & dryer 2x, vacuum cleaner 3x, light bath 6h
  - additionally FR 09:00 washing & drying 1x, light bath 2h
- Others:
  - no light children's room, no computer, no powerful tools
  - pellet heating winter 6h/d (Oct.-March), summer 4h/week (Apr.-Sept.)
  - power-up criterion all lights: dismal weather

FSKNPL HH ... Family with two school-age children, both parents working

- ♣ Two professional adults
- ♣ Working hours 08:00 - 17:00
- ♣ During the week 50% both in the evening at home
- ♣ Weekends 70% at home, 30% on weekend trips throughout the weekend
- ♣ **Cleaning:**
- ♣ Cleaner ... cleaning, washing and ironing once a week during the day
- ♣ Parents ... at weekends at least 2 x washing
- ♣ Holidays 5 weeks a year of which summer 2 weeks, winter 1 week, remaining time at home
- ♣ **Cooking behavior:**
- ♣ Dinner during the week 100%, on weekends 90%
- ♣ Lunch during the week 100%, on weekends 80%
- ♣ Breakfast during the week 100%, on weekends 90%

IMPLEMENTATION

- Holiday:
  - summer 24.07.-07.08. winter 30.01.-06.02
    - all appliances off, except: refrigerator, freezer, pellet heating
  - vacation at home 09.08.-13.08. & 18.10.-22.10.
    - when at home consumption normal except cooking at noon (stove & extractor hood 2x, mixer 1x)
- Weekends: departure FR afternoon, arrival SUN afternoon
  - on the road see calendar (14 weekends per a)
- Breakfast weekdays 07:00 weekends 09:00:
  - coffee machine 1x, toaster 4x, water boiler 2x
- Working hours 08:00 - 17:00:
  - mornings from 6:00 (weekends 8:00): hairdryer 1x, ventilation bath-restroom 2h, light bedroom 1h, light children's room 2h, light bath 2h, light garage 3x, radio 2h
  - evenings (children 20:00, parents 22:00): light garage 3x, light bedroom 2h, light entrance hall 2-3x, light bath 2h, ventilation bath-restroom 2h
- Children at least 1 from 13:00 at home
  - light kitchen 1h, microwave 1-2x, water boiler 1x

  - light living room 13:00-22:00
  - light children's room about 13:00-21:00
- General & leisure activities:
  - computer 28h/week, stereo system 3h/d, TV 5h/d (evenings always 20:00-22:00), 2x/week DVD
  - light restroom ca.16x, light storage room 2-3x, light hobby room 12h/week
  - light outdoor in the evenings 1-2h, light bath 1h, light cellar 0-1h
- Cooking:
  - weekday 18:00: stove & extractor hood 1x (half power due to GLZ), water boiler 1x, mixer 1x, dishwasher 20:00, light kitchen 2-3h
    - if both parents at home (TUE & THU) additionally: cooker & extractor hood 1x
  - 80% weekends 12:30: stove & extractor hood 3x, water cooker 1x, mixer 1x, dishwasher 16:00
- Cleaning WED 9:00-14:00: washing machine 4x, dryer 4x, vacuum cleaner 5x, lights 3h or 3-5x, (coffee machine 1x, microwave 1x):
  - + 2x washing + drying SUN 17:00
- Dinner weekends 19:00:
  - water cooker 1x, microwave 2x, light kitchen 2h
- Others:
  - drilling machine 11x/a, high pressure steam cleaner 03.04, 24.10. each 3h + 2x/month, circular saw 3x6h/a (16th, 22nd and 23rd October)
  - school holidays in Lower Austria (04.01.-06.01., 01.02.-05.02., 29.03.-06.04., 24.05.-25.05., 05.07.-03.09., 27.12.-31.12.): computer, television, stereo system also in the morning (if at home), as well as if parents' vacation at home

FNSKPL HH ... Family with two non-school children, one parent in parental leave

♣ One professional adult, second is in parental leave

♣ Working hours 08:00 - 17:00

♣ During the week both in the evening always at home

♣ Weekend behavior more at home, few weekend trips throughout the weekend

♣ Cleaning lady or parent in parental leave ... 2 x cleaning, 4 x washing and 2 x ironing the week under the day

♣ Holidays 5 weeks a year of which summer 2 weeks, winter 1 week, remaining time at home

♣ **Cooking behavior:**

♣ Dinner during the week 100%, on weekends 90%

♣ Lunch during the week 100%, on weekends 80%

♣ Breakfast during the week 100%, on weekends 90%

♣ **Leisure activities when at home**

♣ Television x hours a week

♣ Computer x hours a week

IMPLEMENTATION

- Holiday: summer: 03.07.-17-07. winter: 16.01.-23.01.
  - if at home same consumption as normal
  - all appliances off, except: refrigerator, freezer, pellet heating
- Weekends: departure FR afternoon, arrival SUN afternoon
  - on the road see calendar (4 weekends per a)
- Breakfast: weekdays 07:00 weekends 09:00
  - coffee machine 1x, toaster 2x, water cooker 2x, mixer 2x
- Working hours 08:00 - 17:00:
  - mornings 6h: hairdryer 1x, ventilation bath-restroom 2h, light bedroom 2h, light bath 3h, light garage 1x, radio 2h
  - evenings: light garage 2x, light bedroom 19:00-23:00, entrance hall 2-3x, light bath 3h, ventilation bath-restroom 1h
- Generally distributed throughout the day:
  - light kitchen & living room always 06:00-23:00
  - water cooker 3x, microwave 1x, mixer 1x

  - computer 20h/week, stereo 23h/week, television 20h/week (evening always 20:00-22:00), occasionally DVD
  - light restroom ca.12x, light storage room 2-5x, light hobby room 2-4h
  - light outdoor in the evening 1-2h, light bath 2h, light cellar 1h
- Cooking lunch:
  - weekdays 12:00: cooker & extractor hood 1x (half power due to GLZ), water boiler 1x, mixer 2x, dishwasher 15:00
  - 80% weekends 12:30: stove & extractor hood 3x, water cooker 1x, mixer 3x, dishwasher 16:00
- Cleaning MO 09:00-12:00 & THU 14:00-18:00:
  - washing machine 2-3x, dryer 2x, vacuum cleaner 3x, lights
- Dinner 19:00:
  - water cooker 1x, microwave 2x
- Others:
  - light children's room daily 08:00-20:00
  - drilling machine 10x/a, high pressure steam cleaner 10.04., 30.11. each 3h + 2x/month, circular saw 3x6h/a (16th, 22nd and 23rd October)