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Renewable Energy Balancing for residential Homes

Konzept für ein Auslegungstool
zur Kapazitätsdimensionierung von
Batteriespeichern für EFH als Energieplushäuser

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Abstract

This project is focusing on "Renewable Energy Balancing for residential Homes". Cost for electric energy is continuously rising. Therefore a positive trend towards self-consumption of decentralized-produced energy can be observed. Renewable sources like photovoltaic or wind are occurring in rather fluctuating manners. To increase the self-consumption storage solutions are needed. Batteries meet the specifications a storage system needs for a residential home. Batteries are small and powerful.

The scope of this project is to find out:

"How much battery capacity is needed for a residential home and how much self-consumption can be achieved with it?"

A MS-Excel-based program-tool has been developed to guide the design process. The main requirement for this tool was to be easy-to-use. A particularity is the user-definable load and generation profiles. Self-consumption can be increased to en-couraging high levels, whenever the renewable energy generation is both frequent and sufficient.

Kurzfassung

Dieses Projekt fokussiert sich auf das „Regeneratives Energien-Management für Wohnhäuser". Kosten für elektrische Energie steigen stetig. Aus diesem Grund gibt es einen positiven Trend zum Eigenverbrauch dezentral erzeugter Energie. Das Auftreten von regenerativer Energie aus Photovoltaik und Wind sind von starken Fluktuationen unterlaufen. Von Nöten ist eine Speicher Lösung, um den Eigenverbrauch zu steigern. Batterien erfüllen als Speicher die Anforderungen von einem Wohnhaus, da diese klein und leistungsstark sind.

Im Rahmen des Projektes ist zu ermitteln:
„Welche Dimensionierung der Batteriekapazität ist nötig für ein Wohnhaus und wie viel Eigenverbrauch kann damit erreicht werden?"

Ein Programm wurde entwickelt zur Überprüfung der Auslegung. Die Anforderungen wurden auf eine einfache und leicht handhabbare Software gelegt. Die Berechnung erfolgt als Besonderheit über eigens anpassbare Last- und Generator-Profile. Eigenverbrauch kann zu einem zufriedenstellenden Maße erhöht werden. Die Bedingung dafür sind fortlaufende und hinreichende Energieerträge von der Generator Seite.

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List of Abbreviations

CAL	Controllable Active Loads
CCPP	Combined Cycle Power Plant
CNG	Compressed Natural Gas
Bat	Battery
DOD	Depth of Discharge
EFH	Ein-Familien-Haus
EPH	Energie Plus Haus
EPH	Energy Plus Houses
EU	European Union
EV	Electric Vehicle
GaS	Gas and Steam (see also CCPP)
GCV	Gross Calorific Value (Brennwert)
GND	Ground potential
GW	Giga Watt peak
HAWT	Horizontal Axis Wind Turbine
HVS	High voltage stress
IC /	
ICQ	Internal Consumption Quote
kWh	Kilo Watt Hour(s)
kWh_{el}	Kilo Watt Hour(s) electric
kWh_{th}	Kilo Watt Hour(s) thermal
kW	Kilowatt peak
LNG	Liquefied Natural Gas
NCV	Net Calorific Value (Heizwert)
NG	Natural Gas
NREL	National Renewable Energy Laboratory
NSD	Nassi-Shneiderman-Diagramm
P2G	Power-to-Gas
PBS	Photovoltaic Battery System
PHP	Pumped Hydrogen Power
PV	Photovoltaic

PVG	PV Generator
PWh	Peta Watt Hour(s)
SFH	Single Family Houses
SOC	State of Charge
SSR /	
SSQ	Self-Sustain Rate / Quote
STC	Standard Test Condition
TWh	Tera Watt Hour(s)
VAWT	Vertical Axis Wind Turbine
VBA	Visual Basics for Application

"We are heading directly for the abyss. […]

The Resources of our Planet are limited."

„Wir fahren geradewegs auf einen Abgrund zu. […]

Die Ressourcen auf diesem Planeten sind begrenzt"

Volker Pispers

1 Introduction

Seven billion people on earth have a huge demand for energy. Per annum mankind generates 19.000 TWh of electric energy (1). We need electric energy in industrial facilities as well as private households. Whether we use it to operate kitchen utilities or computers, it is one of the most convenient forms of energy. Today, most of this electrical energy is produced by the conversion of fossil fuels via thermodynamic processes. However, since the supply of these fuels is limited, alternatives must be incorporated in any future energy concept. To allow for these alternative energy forms to have maximum impact, in terms of replacing fossil fuels and preservation of the environment, mechanisms to balance grid fluctuations are needed. Since alternative sources are not subject to human demand but are rather function of for example wind or solar irradiance, some sort of storage capacity for electric energy has to be installed.

Germany's government passed a new energy policy in 2010. The objectives are efficiency, supply security and environmental compatibility (2). The policy was exceeding the operating times of nuclear power plants. In March 2011 a change of events took place: Fukushima. Germany's eight oldest nuclear power plants were shut down immediately. The nine remaining plants will be shut down step-by-step until 2022. Since subsidies for PV were cut in the beginning of the year 2012 and while energy prices are rising, the self-consumption of electric energy as well as its storage is discussed more frequently by politicians and engineers (3). In 2050 the following parameters shall be reduced (versus year: 1990) (4):

- Greenhouse gas emissions of minimum by 80%

- Renewable energy part by 60 % of primary energy demand and 80 % of gross electric energy consumption

- Primary energy to 50 % (compared to 2008)

1.1 Objective

The objective of the project is to design a software tool according to the residential needs which allows the user to dimension the capacity of the battery storage. Certain steps have to be taken into account. The primary energy consumption of a private house hold is roughly divided in 55 % thermal, 30 % mobility and 15 % electric energy. Thermal heat is grouped in heating and water heating. The thermal expenses can be reduced significantly by an isolation and ventilation system with heat recovery. Electric cars and vehicles (EV) shall cover the new mobility concept. Since charging take place mostly during the night, the distribution grid is not yet ready for EVs. The drivetrain efficiency of EVs compared to fossil fuel powered cars is increased by a factor of two to three. Electric energy usage can be minimized by consumer behaviour and the modernization of low idle demand of residential electronics. Decentralized accumulators in combination with local generators will provide an optimization which will lead to minimisation in grid losses and maximisation of the self-sustain quote (SSQ).

The basic principle of a single family house with a PV Battery System (PBS) is shown in Figure 1-1 (5) (6). During PV off times (night) the battery or/and grid supply/supplies the load. Solar energy efficient to power consumption load: 1) feed into battery 2) feed into grid Solar energy insufficient to power consumption load: 1) battery supplies 2) grid supplies (6) (7)

Figure 1-1:   *PV Battery system feeds consumer or stabilizes grid*

1.2 Methodology

The project followed the KISS approach ("Keep it short and simple"). Microsoft Excel was chosen as program development platform because it is a widespread program all over the world. The language VBA (Visual Basics for Applications) is an easy programming language which can be learned in short time to execute function.

At first most common electric generators and storage units were investigated. For residential homes like single family households (SFH) the range of generators and storage units were limited by state of the art technologies and volume specifications. In the next step information for environmental constraints was looked into deeply by research.

The program development than began with determination of the constraints. The battery algorithm was designed and constantly improved. For further improvement the battery algorithm can be edited and selected in the program. Features and more functions were continuously applied to the program during the development.

In the beginning of this project work only a PV-Battery systems were considered to power the SFH. Other generators and loads were added later on. For validation of the self-sustain quote the results were compared to similar target objects and simulations. Error calculation bandwidth is calculated by uniform Monte Carlo simulation and by a robustness analysis.

A five percentage error has to be applied for the whole simulation in advance (8). Calculating by using 15 minute intervals instead of one minute based values creates this error. The 15 minute interval resolution has been chosen to handle the data as excel files and bring calculation time down.

2 Generators for residential Homes

2.1 General Electric Generators

Generators for residential homes have to fulfil many criteria such as economical reliability, low noise-emissions, certain volumetric dimensions and - for thermal processes – the usability of their thermal energy.

Electric generators supply an electric current to a power grid or a stand-alone off-grid system. Most generators are mechanical motors driven via rotation. The rotation is engendered via turbines, which are put between a high incoming pressure and a low output pressure. Alternatively other thermodynamic engines are applied. High pressure is mostly engendered by burning substances containing carbon dioxide and hydrogen, while low pressure is equivalent to the ambient pressure of the location at site. Some renewable energy sources do not need motors or thermodynamic processes. Renewable sources feature continuous availability and low carbon dioxide emissions. For a list of common renewable energy generators used in residential see Table 2-1.

Table 2-1:   *Renewable energy forms and common generators (9)*

Renewable Energy Forms	Common Generators
(1) Solar	Photovoltaic Module (PV)
(2) Wind	Wind Turbine (HAWT)
(3) Biofuels	Combined Heat and Power (CHP)

For comparison of different electric energy sources the carbon dioxide footprint of the total eco-balance can be viewed in Table 2-2. The eco-balance comprehends data over generator lifetime, maintenance, manufacturing and disposal respectively recycling efforts (9). The negative carbon dioxide emissions for biogas CHP are calculated of neutral biogas emissions by comparison to heating-oil. Biogas and wind have the lowest impact. Photovoltaic depends on location site. In Spain and at latitudes from -45° to +45° irradiance is sufficient with an annual solar energy input of 1500 kWh/m² to more than 2500 kWh/m² (see chapter 2.2 Solar Powered Electric).

Table 2-2: *Specific total carbon dioxide footprint per kilo-watt-hour (kWh) of different Technologies (9)*

Technology Form	CO_2 Equivalents in [g/kWh$_{el}$]
Nuclear Power Plant	32
Natural Gas CHP	49
Natural Gas (Gas and Steam + CHP)	148
Biogas CHP	- 409
Wind	24
Hydrogen (general)	40
PV (Spain)	27
PV (multi-crystalline)	101

2.2 Solar Powered Electric Generators

Solar energy is the most important energy source of all. The outer space surface of earth atmosphere is hit by an average power of $E_0 = 1367 \frac{W}{m^2}$. E_0 is called the solar constant which describes the average power per square meter. The entire earth projected surface is a circle-area of 127.7*1012 square meters which is described by Equation 2-1. The projected surface is 12.5 times larger than Europe and nearly 360 times as Germany.

$$A_{sun} = (\frac{d_{Earth}}{2})^2 \times \pi = (\frac{12,750,000\ m}{2})^2 \times \pi = 127.7 \times 10^{12}\ m^2$$

Equation 2-1: *Projected circle-area representing earth atmosphere surface which is directly hit by the sun*

The entire power input from the sun to earth is given by the multiplication of earth's projected surface by the solar constant E_0. The power summarises to 174.5 Peta-watt (see Equation 2-2).

$$P_{sun} = A \times E_0 = 127.7 \times 10^{12}\ m^2 \times 1367 \frac{W}{m^2} = 174.5 \times 10^{15}\ W$$

Equation 2-2: *Average solar power hitting earth*

Every hour the earth receives 1.22 times more solar irradiance energy than human demand on primary energy for a whole year. (10) ($174.5\ PW \times 1\ h \div 143.5\ PWh = 1.22$) The energy input from sun to earth's atmosphere for a whole year sums up to around 10,660 times the energy of human demand. Human demand can be satisfied by using 0.01 % of solar energy. The sun sends this energy in form of electromagnetic waves carrying photons. Photons cause different environmental effects which

can be used to produce energy. In Figure 2-2 the mean global solar irradiance for every terra firma is shown. The average irradiance power varies from low as under 175 W/m² (1533 kWh/m² per year), shown in blue and turquois, up to over 225 W/m² (1971 kWh/m² per year), shown in red and dark-red.
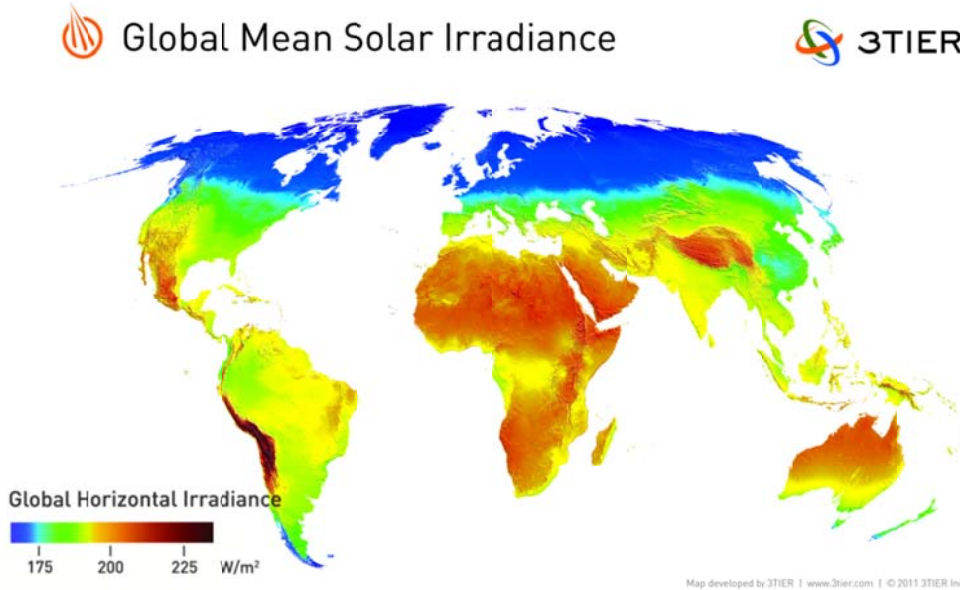
Figure 2-2: *Global mean solar irradiance worldwide from than 175 W/m² (blue/turquois) up to 225 W/m² (red/dark-red) (11)*

2.2.1 Photovoltaic

Photovoltaic is the only energy generation form which accomplishes the direct conversion of electromagnetic waves, containing photons, to electric energy in one step. Photovoltaic modules are exposed to direct and indirect sun light. Charges within the material are separated supplying an electric direct current (DC) to the load. Voltage and current are coherent and variable. Power point trackers are used to operate the PV generator at the maximum power point. The variable voltage and current is then transformed with an inverter to standard alternating current with a given voltage and frequency. For feed into the distribution grid the nominal voltage and frequency is 230 V/50 Hz or 110 V/60 Hz.

Photovoltaic Effect

The photovoltaic effect is based on photons which hit an intrinsic semi-conductor material creating pairs of a free electron and a "hole". The electron and "hole"

charges are separated by the electric field within the semi-conductor. If the semi-conductor is connected to an external power circuit; an auxiliary consumer can be powered (see Figure 2-3).

Shown is a photovoltaic cell with positive (p+) and negative (n+) doped material connected by front and back metal contacts (grey). The + symbol indicates high doping zones. In this particular case only two layers are used.

The sun sends out light-beams containing photons. Photons with the specific energy create a pair of an electron and 'hole' in the intrinsic layer. The intrinsic layer contains an electric field separating the electron and 'hole'. The resistance R is connected to the PV cell. The electron passes through the wires and load. At that point the electron releases its energy. A sunbeam hitting a front contact finger is reflected or if the material absorbs the photon the energy is emitted as heat and is lost.

The electric field in the semi-conductor is within the intrinsic zone. The doping of the semi-conductive material leads to the emergence of the intrinsic zone within the photovoltaic cell. Silicone for example is interspersed with impurity atoms. Silicone has four external electrons. The silicone is doped on the bottom side with boron that has three external electrons leading to a p-doped layer ('holes' in mesh). The front side of the solar cell is doped with phosphorus which has five external electrons leading to an n-doped layer (mesh with more electrons). In case a plus sign (+) is put to the n or p on an exposition the layer is heavily doped, a minus sign (-) indicates a layer of light doping. The creation of an electron and "hole" only occurs if the energy level of the photon is higher than the band gap of the specified semi-conductor material. The band gap is the energy gap between the valence band and the conduction band. In the valence band the electron is bound to the atom, while in the conduction band the electron is free to move. Also the retention time in the intrinsic zone of the semi-conductor has to be short. If it takes the electron or "hole" too much time to leave the intrinsic zone, the possibility of recombination increases. Recombination is the destruction of one electron and "hole". For example, holes move more slowly inside the material than electrons because they are skipping from one atom to another. If one electron is fast enough and hit the 'hole' they recombine and the energy is lost entirely to heat. Energy is also lost by self-shading of the module front contactors.
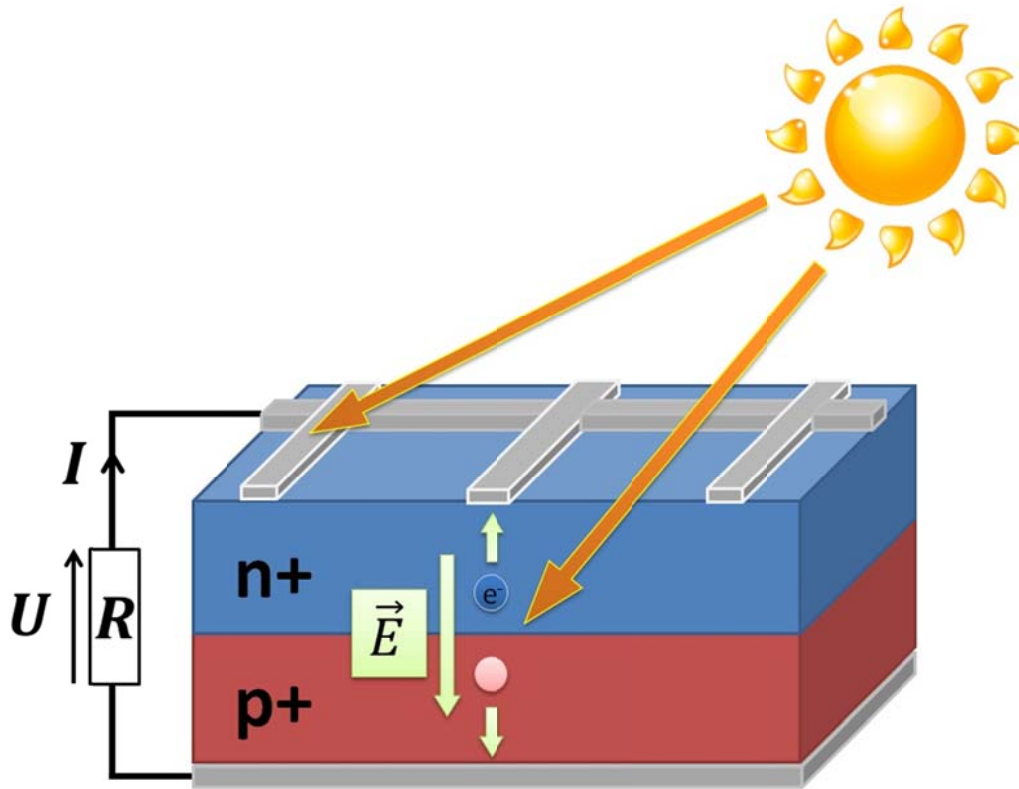
Figure 2-3: *Photovoltaic cell with layout (n/p doped), contacts, electric field and connected load resistance R*

Depending on the band gap and structure of the semi-conductor material the photovoltaic cells absorb different spectrums of light. Different sensitivities are achieved by each material and material composition. For example indium-gallium-phosphorus (InGaP) has a high sensitivity between 350 and 680 nm, gallium-arsenide (InGaAs) between 620 to 900 nm and indium-gallium-arsenide (Ge) 850 to 1600 nm (see Figure 2-4) (12).
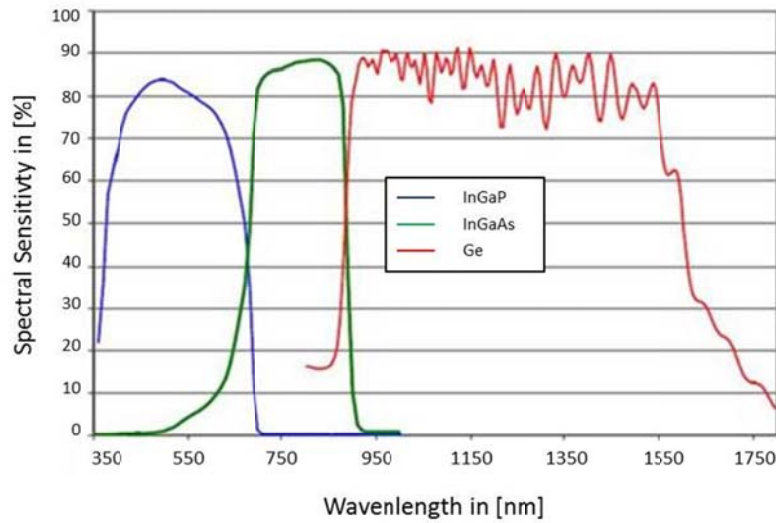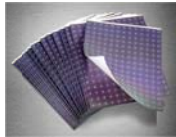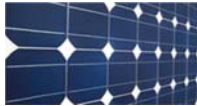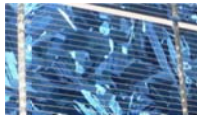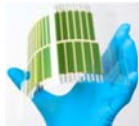
Figure 2-4:   *Spectrum Sensitivity of a Triple Junction Cell (12)*

Energy output from a solar cell is affected by many environmental impacts. It is only available in a rather fluctuating form from morning to dawn, and is dependent on temperature, shading (clouds and near objects), module type, location and tilt of the modules as well as the air mass index (AM). Air mass describes the way a sun beam passes through the atmosphere. An AM factor of 1 describes the shortest way through the atmosphere when the sun stands in zenith, while AM 0 is the extra-terrestrial irradiance.

Cell-Types

Basically there are five different photovoltaic cell-types (see Figure 2-5 to Figure 2-10):

Cell Type	Notes	Efficiency Common - Lab	Picture
Amorphous	Non-structured material, very thin layers, transparent conductive oxide (TCO) front contacts, no frame, glass front and back, cheap	8 % - 20 %	 ***Figure 2-5:*** *Copper Indium Gallium Selenium Amorphous Module; size 1.2 m x 0.6 m (7)*
Printable ***Figure 2-6:*** *Printable Liquid*	Printable liquid, non-structured material, printed on metal foil by roll-to-roll procedure, fast, under testing conditions		 ***Figure 2-7:*** *Printed Cells (13)*
Mono Crystalline	One crystal extracted from molten silicon, high costs	20 % - 25 %	 ***Figure 2-8:*** *Mono Crystalline PV Module (14)*
Poly Crystalline	Multiple crystals cast-material, low sawing losses, efficiency up to	16 % - 20 %	 ***Figure 2-9:*** *Poly Crystalline (15)*
Organic	cheap, non-toxic, short lifetime	5 % - 8 %	 ***Figure 2-10:*** *Organic Cell (16)*

2.2.2 Wind

Wind is an indirect conversion of solar. Solar irradiance heats up the air and ground on earth. The sun lights a mean percentage of about 50 % of earth. One side heats up while one other cools down. Also different surface materials have different reflection grades called the albedo factor (see Table 2-3). And with different heights and different air mass factors, air is heated up to different pressures which results in air movement. The global mean wind speed is one indicator of how good a site is for a wind power generator installation (see Figure 2-11) (17). Wind power output is dependent on the cubing of wind speed ($P_{wind} \sim v_{wind}^3$).

Table 2-3: *Albedo Factors: Albedo factors describe how much light is reflected from an object. (18)*

Environment	Albedo Factor
Cumulus	75 %
Cirrus	20 … 40 %
Water	8 %
Gras	20 … 25 %
Wood	5 … 10 %
Snow (fresh)	80 … 85 %
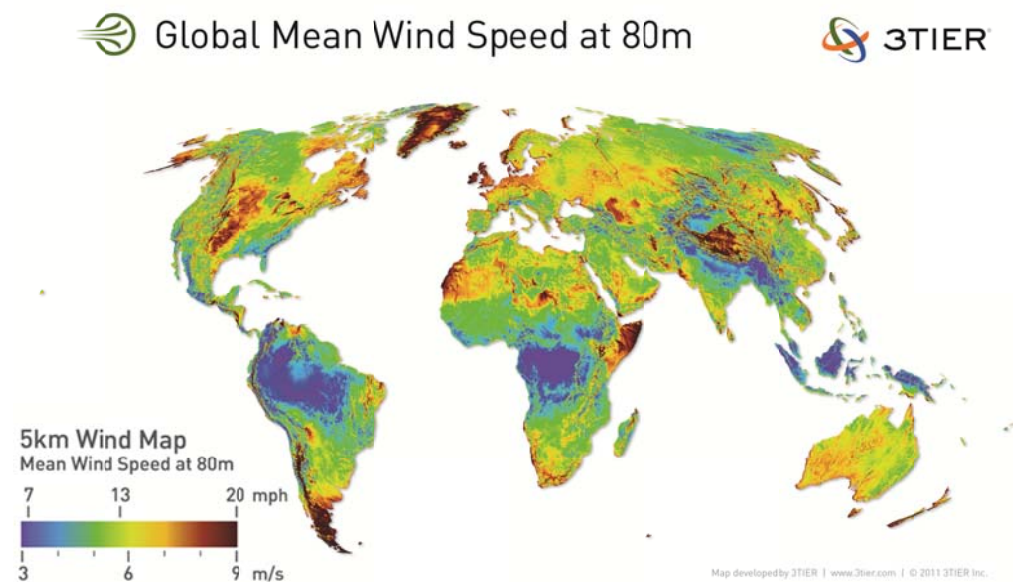
Figure 2-11: *Global mean wind speed at 80 m height (17)*

Small wind turbines are predestined for roof top installation at free-standing houses or at masts in a field in the countryside. The wind is blocked by the house concentrating a high air flow over the house. Micro wind turbines are available from 500 W_{el}

to 5 kW$_{el}$. Wind achieves 2000 to 2500 h operation time per year and is more linear fluctuating all year long than PV (see Figure 2-12).
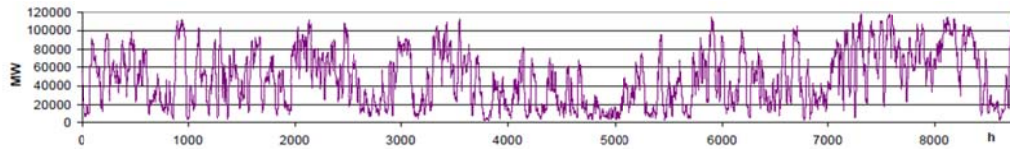
Figure 2-12:   *Wind power transmission grid of a total year: Fluctuating with high peak power and enormous drops and increases in power output. (19)*

2.2.3 Biomass and Biofuels

Biomass is processed from plants to use as thermal charges. Biomass can be directly used (e.g. wooden chips) or by fermentation to biogas and other processes to fuels such as alcohol (methanol) and diesel. Biofuels are renewable fuels out of biological plants. Wood, maize, rape and sugar beets are the most common renewable resources for the production. They are grown by photosynthesis while absorbing carbon dioxide (CO_2) from the air. Meanwhile the second generation fuels are made as like methane, synthetic liquefied, ethanol or kerosene. Biofuels can be directly used in standard motor, turbine or heater types. In any terms specific machines must be adjusted and require testing. The machines should be certified for running on the specified biofuel. Powering a combined heat and power micro plant at home natural gas as well as purified biogas can be added to a heating system in combination with a peak load boiler (see Figure 2-13). In future also technical produced fuels can be applied (see chapter 3.3).
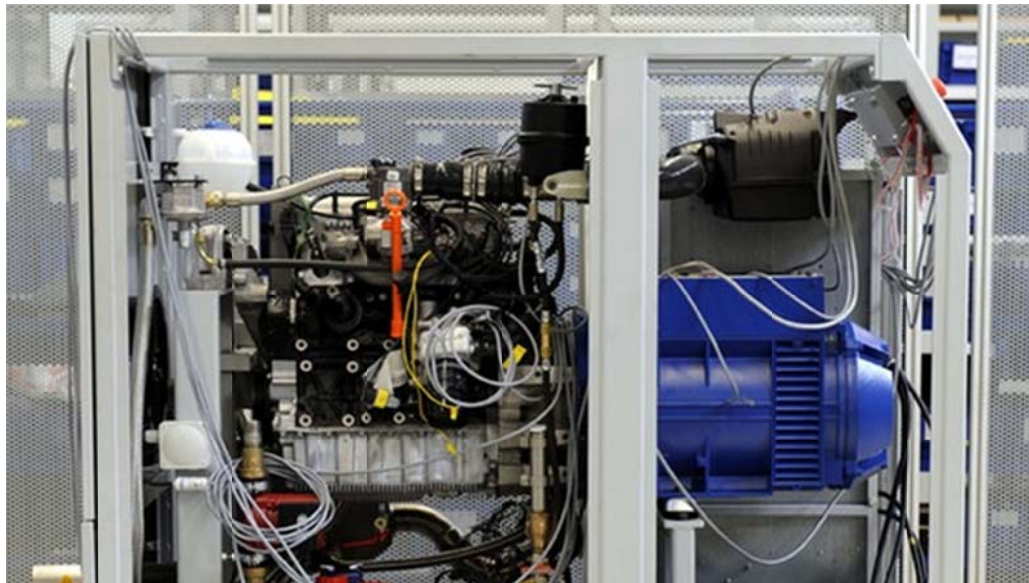
Figure 2-13:   *Combined heat and power plant with a two litre VW natural gas four piston engine "ZuhauseKraftwerke" Supplier: Lichtblick (20)*

3 Storage Types and Active Loads

3.1 General Storages

An overview on electrical storages in general and a more specific look into chemical batteries and fuels will be given. For residential homes there is a need for seminal and promising technologies with high efficiency and affordability. Storages are systems which allow charging electric energy into a kind of bucket and discharging it again as needed. The electric energy flow is transferred to another energy form, like potential, kinetic, chemical, static electrical or magnetic fields or warmth energy. Each conversion is associated with energy losses. An overview of several different storage types and their capacities is shown in Table 3-4.

Table 3-4:   *Energy Storages Overview*

General Energy Form	Energy Storage	Capacity	Energy Density	Efficiency	Costs	Notes
Potential and Kinetic	Hydraulic Hydro Energy Storage	Weeks	Medium	75-85%	Low	Eduard Heindl (21)
	Hydroelectric water	Weeks	Low	75-85%	Low	Flooded Area enormous
Chemical	Electrolysis	Weeks	High	~45%	Medium	Diffusion problems within storage applications
	Methanation	Months	High	~35%	Medium	Usage of existing Pipelines
Electro Chemical	Lead-Acid / NiMH / Li-Ion Batteries (solid)	Days	High	70-90%	High	Expensive (2012)
	Redox Flow battery (fluid vanadium)	Days	High	70-90%	High	Expensive (2012)
Kinetic Pressurised and Rotational	Compressed Gas (Air)	Hours	Medium	50-75%	High	Economic with salt caverns
	Flywheel	Minute Reserves	Medium	95%	High	High cycle-stability

13

General Energy Form	Energy Storage	Capacity	Energy Density	Efficiency	Costs	Notes
Electric or Magnetic	Capacitors	Seconds	Low	99%	High	Very high cyclestability and cost
	Super Conductive Coils	Seconds	Low	99%	High	Cooling requirements

green – optimal, yellow – acceptable, red – unacceptable

Chemical Storages

During the project only chemical storages are considered for the conversion of electric energy. Chemical storages feature high energy density. All other storages are unlikely to even fit in a residential home due to volumetric reasons. There are two opportunities to store electric energy in chemical boundaries:

- Batteries
- Fuel

3.2 Batteries in General

Batteries are galvanic elements which can be subdivided in primary and secondary elements. Primary elements are not-rechargeable and some examples are shown in Figure 3-14. On top a battery is shown with a spill, the coin shaped one is lithium based and at the left bottom corner with to connections on one side is a 9V block battery (6 cells series). Secondary batteries are accumulators and rechargeable Figure 3-15. The LR06 or also AA accumulators are from Sanyo (line called eneloop; nickel metal hydride) and the flat mobile phone lithium accumulator manufactured by Polarcell has a capacity of 1600 mAh (lithium-ions). In the following batteries are confined to be accumulators.

Figure 3-14: *Primary Batteries*

Figure 3-15: *Secondary Batteries*

Batteries have a plus and a minus pol which supply a nominal voltage (e.g. Lead-Acid-Battery 2 Volt). The nominal voltage is dependent on the material of the electrodes (anode and cathode). Depending on the resistance of the connected load a direct current and voltage is supplied. The electrodes have different electro potentials. Wired to a load the materials want to react to reach a lower energy state (more stable). Two galvanic half-cells are connected with a conductor (from anode to cathode) and via an ion-connection. One material has to be nobler than the other. The chemical process is called redox reaction. One material is oxidized while the other is reduced. The electrode material which is oxidized is the anode; the substance which is reduced is the cathode. For an easy understanding: In case the electro-potential of the anode is negative (or more negative than the cathode) there are more free electrons by the anode than by the cathode. If the electrodes are conducted via a load this electron disequilibrium wants to balance to get into a matching state. As an example the Daniell-element is shown in Figure 3-16. The Daniell-Element contains a zinc anode, copper cathode, ion-connector and a volt-meter. Copper is nobler than Zinc. More free electrons are available at the anode Connected to a load the electrons want to get into an equilibrium state. The electrolyte is an ion-exchange helper between the two dissolutions. Modern batteries use a solid electrolyte.
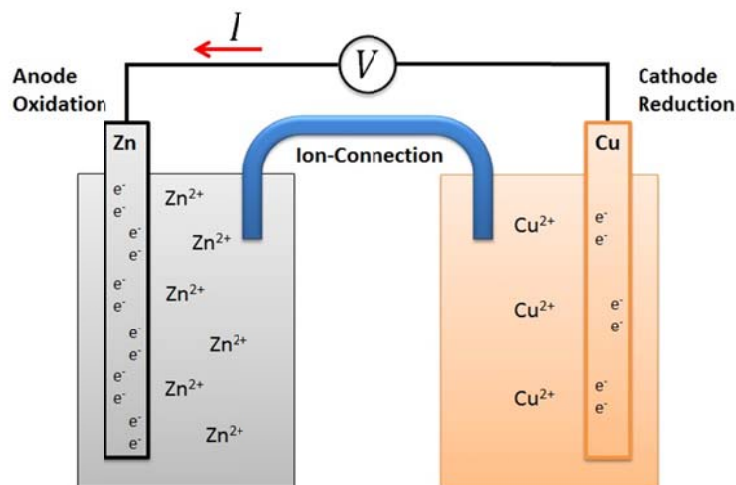
Figure 3-16: *Daniell-element with volt-meter and ion-connection bridge*

The basic principle of a Daniell-element battery in basic electric circuit diagram is shown in Figure 3-17.
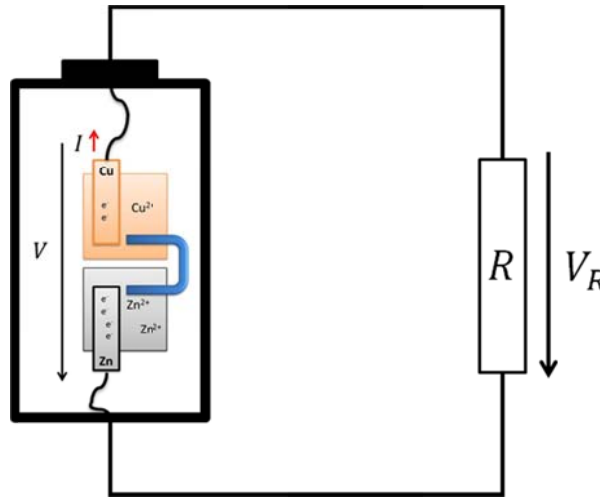
Figure 3-17: *Electric Circuit Diagram powered by a Daniell-element as voltage generator supplying a resistance R*

3.2.1 Battery Types

The most sold batteries are based on lead-acid, nickel metal hydride or lithium-ions. All batteries need further improvement in energy density (kWh/m³ ratio as well as kWh/kg ratio) and security development. Fundamental research is mainly focusing on improving energy density which can be improved by choosing different electrode materials and structures. A comparison of the state of technology can be found in Table 3-5 (22) (23) (24). Energy density rise will have positive effects for mobile as well as residential applications and general a better economic price ratio.

Table 3-5: *Comparison of different battery types (22) (23) (24)*

Battery Type	Voltage per Cell	Energy Density in [Wh/kg]	Power Density [W/kg]	C-Rate in [h^{-1}]	Cycles	Prize in [€/kWh]**
Lead	2 V	25 … 40	70 … 150	2 … 4	250 … 750	150
Nickel Metal Hydride	1.2 V	65 … 100	120 … 1500	2 … 25	> 1000	600
Li-ION	3.7 V *	Up to 200	up to 5000	2 … 100	> 2000	800 (today)

*   Cathode: graphite; Anode: LiMnO2

**   C-Rate: Specifies how fast the battery is (dis-)charged.   For example:

C-Rate 2 h-1 → $Discharge\ Time = \frac{1}{C-Rate} = \frac{1}{2\ h^{-1}} = \frac{1}{2}\ h$

Lead-Acid

Lead batteries are world-wide the most applied battery form. Almost every fossil fuel powered vehicle is started with a lead battery. Nominal Voltage per cell is two volt. Energy density is quiet low with 25 - 40 Wh/kg. Lifetime is achieving 750 cycles. In Equation 3-3 the chemical equation for a lead battery is given. The lead-anode is oxidized; the lead-dioxide-cathode is reduced. The electrode materials are in solution of sulphuric acid (H_2SO_4).

$$PbO_2 + Pb + 2\,H_2SO_4 \;\leftrightarrow\; 2\,PbSO_4 + 2\,H_2O$$
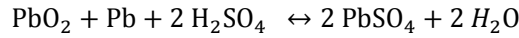
Equation 3-3:   *Lead Acid Battery Chemical Equation: Discharging reaction left to right side; charging reaction right to left side*

Nickel Metal Hydride (NiMH)

Nickel metal hydride has a great advantage over the predecessor technology with nickel cadmium. It is more environmental friendly and contains no toxic cadmium. The nominal voltage is 1.2 V. For quick discharge application with high currents nickel cadmium batteries are more suitable. Common forms of application are standard LR6 batteries for low discharge rate electronics and mild to full hybrid cars. The chemical reaction is shown in Equation 3-4. Electro potentials are -0.83 V for the metal and +0.49 V for nickel. Nickel Metal Hydride has a life time over 1,000 cycles.

$$NiO(OH) + MH \leftrightarrow Ni(OH)_2 + M$$
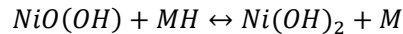
Equation 3-4:   *Chemical equation nickel metal hydride battery: Discharging reaction left to right side; charging reaction right to left side; M stands for metal*

Lithium-Ion

Lithium-Ion is a whole group of different battery types with different voltages. Lithium-ions are the ions which migrate from the one electrode to the other. One common electrode type is a graphite mesh; the other is a lithium-metal with additives. The voltages diverse between 3.3 and 4.2 V Lithium-ion battery lifetime is over 2,000 cycles. The biggest disadvantage for Li-Ion batteries is todays prise. The chemical reaction of a lithium battery with a cobalt-oxide cathode is shown in Equation 3-5 (25).

$$Li_X C_6 \; + \; Li_{1-x}CoO_2 \;\leftrightarrows\; 6C + LiCoO_2$$
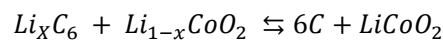
Equation 3-5:   *Chemical equation of a lithium battery with cobalt-oxide-cathode*

3.2.2 Lifetime Constraints

Lifetime is defined over the capacity loss of the battery. After a certain usage time and cycling, the battery losses are 20 % in capacity and in some cases also other abilities are reduced (e.g. high current stability). Lifetime for modern batteries should be 10 to 20 years under normal cycling. The lifetime has many dependencies. In the following cycling, temperature, storing, voltage and current as well as volumetric work are looked at in more depth (26).

Cycling

Cycling tests are progressed with a limited Depth of Discharge (DoD). Also battery stress may be optimized by charging. In Figure 3-18 a constructed graph for a lead acid battery is shown illustrating the cycling times over the discharge depth. This distribution is similar for many battery types. The energy throughput is higher when cycling with lower discharge depths. In terms of micro cycling, DoD is in single digit percentage range, the energy throughput is much higher.
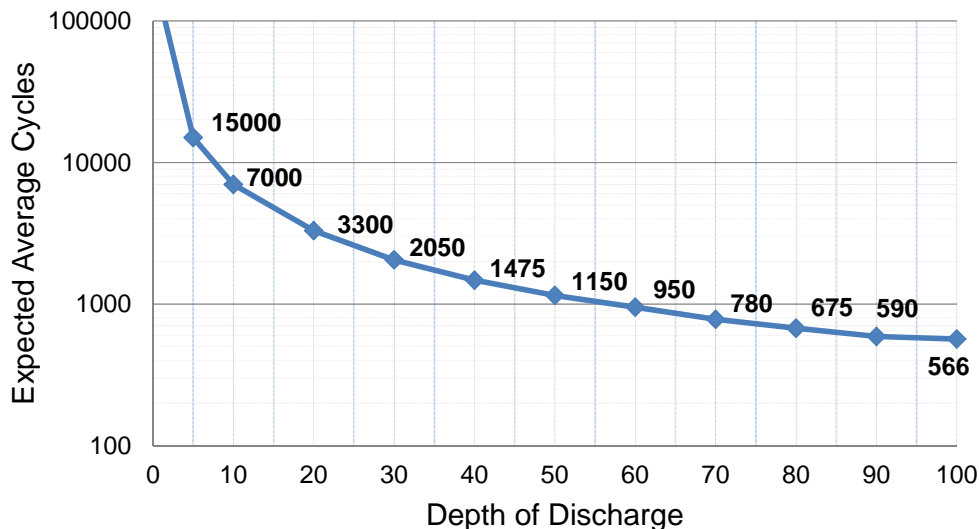
Figure 3-18: *DoD versus Cycling Lifetime: In case of micro cycles the energy throughput can be increased significantly (26)*

Temperature

Generally said temperature influences the battery significantly. The higher the temperature, the energy supply ability of the battery and capacity loss is increased. Concerning lifetime high temperature means a reduced lifetime (see Figure 3-19). Lifetime over battery temperature: Higher temperature equates to shorter lifetime

expectation. Red line shows battery operation at 35°C, green line 25°C and the blue line 15°C operation. During operation with 35 degrees Celsius the battery can store up to 20% more energy during the first 10 years compared to 15 degrees Celsius. At 15°C the battery lifetime is 35 years to still hit 80% capacity. The minimum temperature is limited by the electrolyte (e.g. electrolyte freeze point) and requirements on minimum capacity and power output (26)
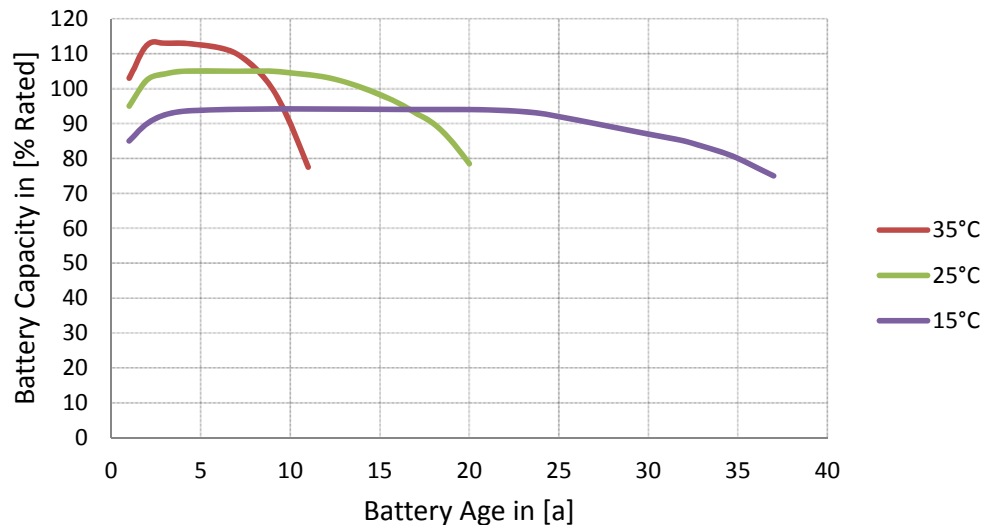
Figure 3-19:   *Lifetime of a lead battery over temperature: Higher temperature equates to shorter lifetime expectation. (26)*

Storing

If batteries need to be stored the self-discharge has to be taken into account. The battery should not be stored in critical conditions. A low self-discharge rate is good for storage conditions. If batteries have a high self-discharge rate they should be charged regularly to prevent deep discharge which not only might cause significant capacity losses, but can even lead to the destruction of the battery. For storing a battery an ideal place in a house is the basement. The temperature is nearly constant between 7 and 25 degrees Celsius. The capacity is limited but the lifetime is increased by the adequate temperature.

Voltage Limitations

Voltage influences the maximum reachable capacity. During cycling the battery high voltage means high stress to a battery. More electrons are separated from the cathode to the anode. For example a lithium battery charged with an end charging voltage of 4.3 V instead of 4.2 V will show that the capacity is diminished to 800 mAh in

200 cycles instead of 350 cycles (see Figure 3-20). Charging the battery with a high voltage increases the stored energy. Number of cycles is diminished significantly.
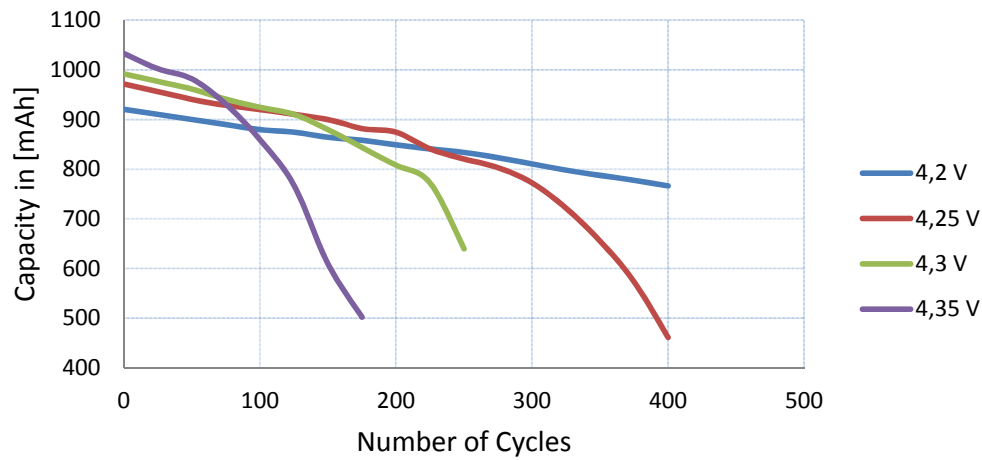
Figure 3-20: *Capacity losses by different charging voltages over number of cycles (26)*

Current Limitations

High currents determine higher losses in the battery. The inner resistance rises with temperature. Temperature is risen by higher discharge and charge currents. Also the cultivation of dendrites will be raised. Dendrites are electrode material which will permeate the electrolyte material and may lead to a considerably reduced insolation characteristic of the electrolyte. The cluster will spread even faster and quicker when they are created. The capacity loss over cycling time at different charge and discharge currents is shown in Figure 3-21. Charging the battery with high currents increases the inner resistance and the thermal losses.
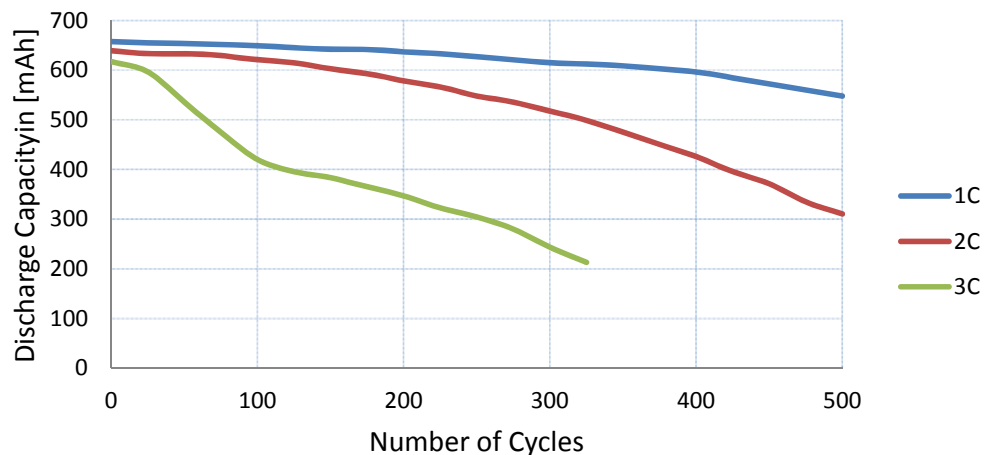
Figure 3-21: *Influence of different charge and discharge currents over cycle stability. (26)*

Volumetric Changes

Another effect is volumetric changes by charging and discharging. For a lithium-ion battery with a graphite and lithium-cobalt-dioxide electrode the battery expands mechanically by around 10 %. To do full cycling (discharge completely -> minimum SOC) the battery is extremely stressed while the volume is changing. Lithium-metal-phosphor-quad-oxide electrodes have the advantage that they shrink in the same ratio as the graphite electrode expands its volume and vice versa. The total expansion of the battery is smaller one percent. The lifetime for that reason is higher. Since the volume changes due to temperature, the packaging has to implement many criteria.

3.2.3 Packaging

Due to the volumetric changes (chapter 3.2.2) and requirements on the usage case, the packaging has to be well designed. For EVs the battery has to be packed in a robust box which must be conditioned. For residential homes the battery should fit through standard doors, should be separated in packages that one or two persons can carry and feature high operator protection guidelines. It must follow the changes of the inner material without producing leaks or damaging the package and has to withstand typical environmental conditions as well as accidents. Regularly an accumulator should be conditioned to increase the life time of the batteries.

3.2.4 Discharging and Charging

Discharging

Discharging the battery has certain criteria. The maximum depth of discharge (DoD) value shall not be under-run. The state of charge (SoC) in this case is at its minimum. End of discharge is defined by the minimum voltage which is dependent on the battery technology. If the battery is connected to a load, the voltage drops because of the non-linearity of the battery inner resistance. Also the temperature influences the battery voltage. To measure the correct value the Idle-Voltage has to be measured. For some milli-seconds idle conditions are engendered and measured. The discharge has to be disrupted when the voltage is under a certain minimum voltage as well as in high load cases to secure the battery from damage. For residential homes the battery capacity has to be well designed. Its capacity shall be large enough that a discharge rate of 1C (1D in some literature) will not be exceeded (see chapter 3.2.2). For example: In case the stove, oven, microwave, toaster, both hair dryer, washing machine, cloth dryer, dishwasher would be activated at the

same time, the maximum load would be approximately 15 kW. Residents cannot or should not use all high power loads simultaneously. In 2012 battery systems are sort of pioneer work, batteries are proven to function and work stable. Prices are high. To store one kWh costs 34 cents minimum for lead batteries (27). If the electricity is consumed from a PV generator or grid another 25 cents can be added (accumulated: 59 cents). Even a natural gas generator can supply cheaper energy in 2012. In case efficiency is 25 %, 4 kWh_{th} gas energy are needed to produce 1 kWh of electricity. One kWh gas currently costs 6 cents. 24 cents would be the cost for the gas for 1 kWh_{el}.

Charging

In case of charging the nobler electrode material is oxidized, the less noble one is reduced. At the anode the oxidation process takes place, at the cathode the reduction process occurs. For reaching maximum state of charge (SoC) there are many techniques for charging. The most common charging procedure is the IU-Version. At first a static current with ranging voltage is applied. By charging the voltage rises and when a certain criterion is reached the charging process is switched to a constant voltage with ranging current. One criterion to switch from constant current to voltage-charging is reaching a certain voltage value, another one would be time, but the latter is rather imprecise. The charging procedure for a battery system in combination with PV and several loads will have to conquer with highly fluctuating characteristics. Charging is stopped if the current under-runs a minimum value (see Figure 3-22). Also the energy supplied to the battery can be measured as a further criterion.
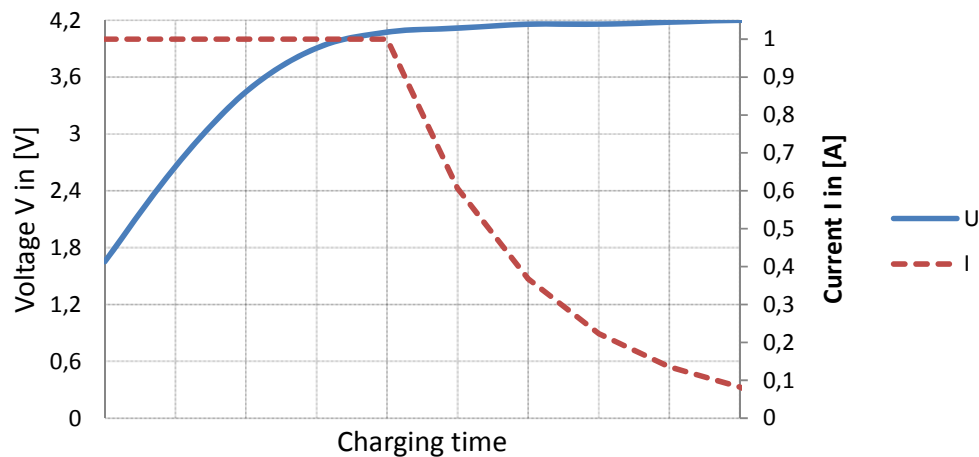
Figure 3-22: *I-U-Charging Curve: If the specified voltage is reached the constant-current charging is switched to constant voltage charging.*

3.2.5 Efficiency, Energy and Capacity

Efficiency

The efficiency of a battery is defined by the discharged energy to the charged energy (see Equation 3-6). To measure the efficiency, at every time voltage and current have to be measured.

$$\eta = \frac{E_{discharge}}{E_{charge}} = \frac{\int\left(U_{discharge} \times I_{discharge}\right)dt}{\int\left(U_{charge} \times I_{charge}\right)dt}$$

Equation 3-6: *Efficiency of a Battery – Discharged to charged Energy (28)*

Energy and Capacity

The capacity or stored energy is defined and measured differently. Instead of energy normally the capacity is given in ampere hours (Ah) which is a rather imprecise value for the really stored energy. The charged and discharge charges describes the storage capacity but not the energy which the battery has powered. Since the voltage is diminished when the battery is attached to a load, its efficiency is lower. The energy which can be used is dependent on all factors discussed in chapter 3.2.2.

3.2.6 DC or AC Bus connected Batteries

Residential homes are often combined with photovoltaic systems. At this system it has to be decided to connect the battery with DC/DC-inverters to the DC bus of the photovoltaic. Alternatively, the battery can be connected to the AC bus side together with the loads or/and additional generators (see Figure 3-23). The advantage is the cheaper solution for the DC/DC-inverters and the use of the DC/AC-inverter of the PV-system. The meter set up is coupled in after the PV-inverter. The energy losses will not be subsided while charging and discharging the battery. The disadvantage is that the battery can't be charged during low power seasons by the grid or additional generators. An AC battery system is shown in Figure 3-24.
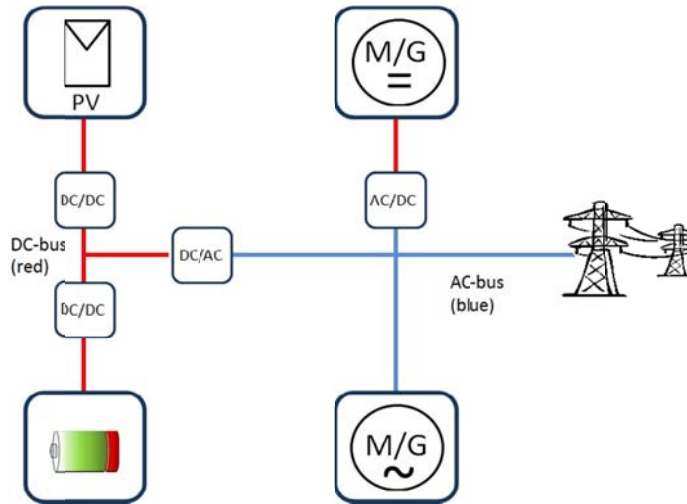
Figure 3-23: *DC/DC Connection of battery to the system. Advantage: high Efficiency. Disadvantage: PV generator only energy source for charging.*
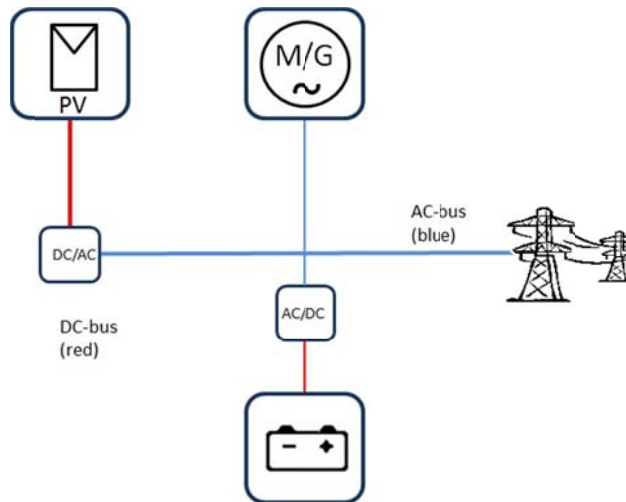
Figure 3-24: *Battery connected to AC-Bus: Advantage: System flexibility, stability and charging from grid. Disadvantage: Two inverter, higher costs.*

3.3 Fuel Storage

Fuels have a high energy density and are well utilisable for storages. Fuels can be transported easily and stored in vast amounts. For long time storages batteries are very expensive today. Tanks for fuel can be integrated all over the fuel distribution network. Electric efficiency of generators varies from 15 % to 30 % for residential application and 60 % for natural gas and steam power plants. By using the thermal energy residential systems achieves efficiencies over 80 %. The fuel can also be used in vehicles which are powered by fuel only as well as in combination with an

EV to extend range by recharging the battery or as heating applications to conserve the battery.

Analysis

Fuel analysis describes the extraction or parting of one material in more substances. Benzene, diesel and kerosene are refined from mineral naphtha. Renewable energy fuels like biogas are also analysed. Biogas is produced by fermentation. The compounding has different qualities, depending on the used biological materials, and has to be processed and refined.

Synthesis

Fuel synthesis describes the conversion from two or more raw materials to useable fuels. As an example bio-diesel is processed via trans-esterification mostly out of raps-oil. In future methane will become a synthesized fuel. It is produced using electrical energy.

3.3.1 Future Fuels

The demand of fuel produced by non-mineral-naphtha-based will rise over the next decades since the time of the peak oil has passed. The supply will decrease and demand will rise. The demand will not be saturated by biofuels since it stands contrary to the food production. Another type of synthetic fuels has to be manufactured. A totally technical produced fuel. Two options for fully technical produced fuels are available: Hydrogen and methane.

Hydrogen (Decomposition)

Hydrogen is produced by decomposition of water. Hydrogen is separated from oxygen using electrolysis. The voltage of the electrolyser depends on the used process (e.g. the voltage can be reduced by using an alkaline dilution). To engender electric energy, fuel cells or modified combustion engines can be used. Gas turbines can be adapted to use hydrogen instead of natural gas. The storage of hydrogen and transportation of large hydrogen quantities has not yet been cleared.

Methane (Synthesis)

Methane can be mixed with natural gas in a huge variety. The storage capacity in Germany accumulates to 200 TWh of thermal energy. Methane can be fabricated out of hydrogen and carbon dioxide. The process is called methanation. In Germany the technical synthesising of methane is promoted by the German federal ministry of environment, nature conservation and nuclear safety and developed by ZSW, Fraunhofer Institute and SolarFuel. The project is called Power-to-Gas (P2G). The sorts of technologies are still in a precommissioning inspection state. Excess electric energy from wind or photovoltaic should be used to convert electric power to methane. Overall efficiency is down to 35 % by using combined gas and steam power plants and if thermal energy is wasted (29). A look-out on the P2G technology can be found in chapter 7.2.

3.3.2 Usage of Fuels Micro Combined Heat and Power Plants

Future micro combined heat and power (µCHP) plants are generators which supply electric and thermal energy to the home. Standard sizes are one half up to five kW_{el} and 15 kW_{th}. These systems will cover a major role in self-sufficient homes. Small energy backup systems are useful to minimize overall cost due to savings relating to the energy supply company. Small generators will help to fit the high balancing need, to stabilize the grid and increase the internal consumption rate as high as 100%. Warmth is required all year long for heating up drinking water and in winter for heating the accommodations. The µCHP systems can be based on a Stirling or combustion engine. The systems can be designed to accept multiple fuels like natural gas as well as hydrogen. Another great opportunity is wooden-chips or pellets. µCHP will be powered by wood, natural gas (biogas or synthesized) or hydrogen.

Natural Gas

Natural gas distribution system is even as large as the power distribution system and widely spread over whole Germany. The power grid supplies no storage capacity (0,040 TWh_{el}). The gas distribution system instead offers an enormous storage capacity of around 200 TWh in Germany. Natural gas (NG) sterling engines advantages and disadvantages will be found in Table 3-6.

Table 3-6:   *Advantages and Disadvantages of Natural Gas*

Advantages +	Disadvantages -
Installation almost everywhere	Installation Cost
Low maintenance cost	Lower efficiency
Subsidy 5,11 €cent/kWh_{el}	Connectivity to Internet

Hydrogen

Main advantage of hydrogen (H_2) is the absolute non-toxic combustion. There are no carbon dioxide emissions while burning. Natural gas (NG) got low carbon dioxide ratings, the ratio between carbon and hydrogen is 1:4. For residential home applications hydrogen tank can be more voluminous compared to mobile applications in cars. Storage size can be done with low specific energy density metal hydride (MH) materials which are able to store 1 - 4 % kg(H_2O)/kg(MH). In Table 3-7 a comparison is shown between hydrogen (H_2) and methane (CH_4).

Table 3-7:   *Comparison between hydrogen and methane*

H_2	CH_4
Storage -	Storage +
Sterling engines and combustion engines	Sterling and combustion engines
Transportation -	Transportation +
High efficiency +	Moderate efficiency
Fuel Cell available	Fuel Cell available Carbon is split from CH_4

4 Fundamentals for the PV-Battery-Tool

The Fundamentals for the PV-Batter-Tool chapter will give an overview about the important backgrounds in environmental as well as political constraints and the program development which were applied to this project.

Up front there is a short overview of a PV-Battery system (see Figure 4-25). It is shortly described how the battery and grid interact with the system (30).

(1) PV Generator

(2) Inverter

(3) Feed In Meter

(4) Two Way Meter

(5) Battery
-Storage of excess energy, if demand is already taken care off
-Power demand, if generation is sufficient

(6) Grid
Full battery:
- Feed into grid
Empty battery:
- Power demand via grid

(7) Consumer

Figure 4-25: *PV-House with added Battery and Grid*

4.1 Potential of PV-Battery Systems

As an introduction two charts are shown to demonstrate which potential impact a battery system has to improve the internal consumption quote (ICQ). Figure 4-26 shows the internal consumption rate in percentage scale dependent on the useable battery capacity of kilo Watt hours. The chart is calculated for a residential home with a load and generation of 5000 kWh. The ICQ rises to a maximum value of 74 %. The minimum with no battery system is 35 %. In Figure 4-27 the increase of ICQ is shown. This chart is meant for economic analysis. The total cost per added kWh can be reckoned and compared to the increase of ICQ. Example: The ICQ is 8 percentage points higher when using a one kilo watt hour sized battery instead of no battery. The result is 35 % + 8 % equals 43 % ICQ. Values have to be accumulated for the total percentage point raise.
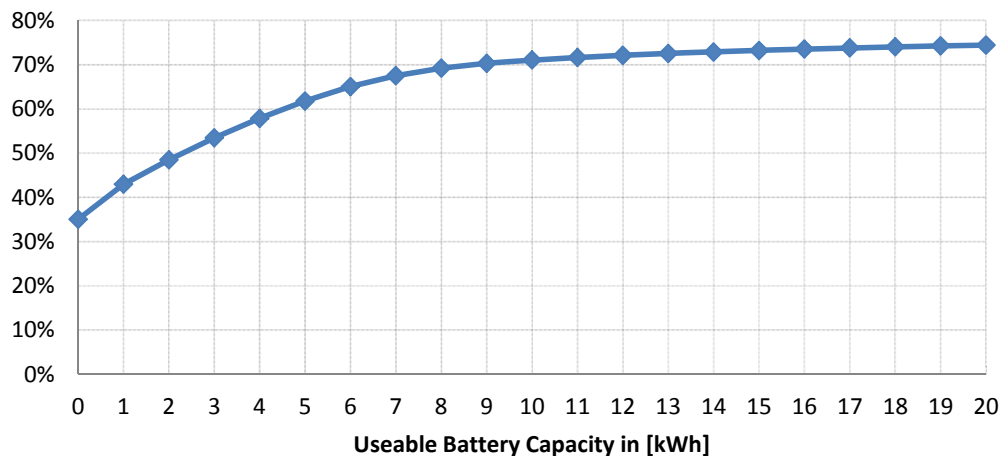
Figure 4-26:   *Internal Consumption Quote over Useable Battery Capacity*
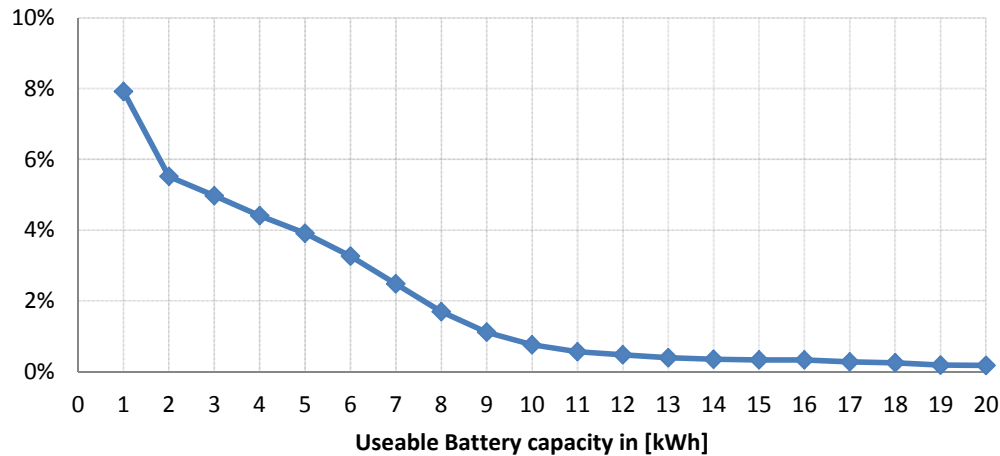
Figure 4-27:   *Increase of ICQ in percentage points over the battery size.*

4.2 Basic environmental Constraints

In the beginning the constraints which should be implemented in the program was identified. A special look was taken at the photovoltaic (PV) and the combined heat and power (CHP) law. For these generators the limitations are well known. As for mini wind power systems there are no limitations except regulations from the ministry of building authorities. The building authorities must approve the location for erecting of the wind tower.

4.2.1 EEG and KWK-G Subsidies

The EEG (Erneuerbare Energien Gesetz) is the German law for renewable energies. EEG subsidies were cut by ~30% in Q1/2012 for regular rooftop-mounted PV generators up to 30 kW. The power is subsided with different rates for power fed into grid and the energy used at home by one-self. Since energy prices are rising to increase internal consumption becomes more reliable and self-sustaining systems more reasonable in the future.

KWK-G (Kraft Wärme Kopplungs Gesetz) is the German law for combined heat and power generators. CHP up to 2 MW are subsided with 5.11 €cents/kWh plus the price on the EEX market by the KWK-G. In the first 5 years after installation an add on of 2 ct/kWh is paid for electricity.

4.2.2 Photovoltaic 70% Cut

PV generates enormous peak power without any practical energy supply. Cutting the performance to 70 % will help to smooth the energy fed into grid with minimal impact to the energy yield. The EEG2012 law requires a 70 % cut off or a cut of control even for small plants up to 30 kW.

As shown in Figure 4-28 the energy loss by cutting the rated module to inverter ratio to 70 % is as low as 5 %.
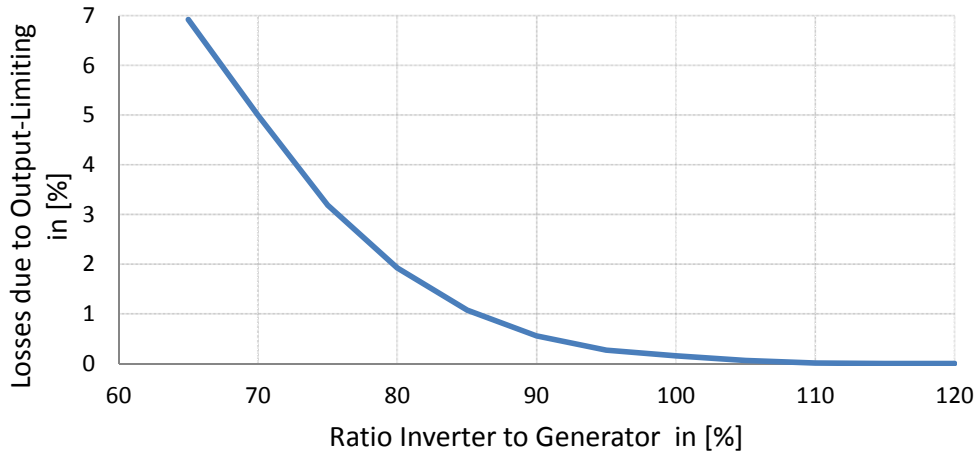
Figure 4-28:   *Energy losses of PV/Inverter ratio: At 70 % ratio the losses accumulates to 5 % (31)*

Since PV modules become cheaper while playing a smaller part in the overall purchase costs, there is the opportunity to select another PV / inverter ratio. The PV / inverter ratio is described as ratio between the PV modules rated power to inverter rated power. For example a ratio of 0.9 defines that 900 W (rated power under STC) is installed on an inverter with max power 1000 W. In future more and more plants will be installed "oversized" with ratios over 1.43 or even more. 1.43 occurs when considering the 70 % cut. Instead of cutting down the inverter to 70% size the PV modules are increased to one divided by 70 % equals 1.43. The excess energy generated by "oversizing" the modules must be used instantly.

One practical, elegant and cheap solution is to use this excess energy by heating up water with heat elements. Further options are to extend fridges with an added storage for cold or even use a heat pump.

Alternatively the generator can be equipped with a remote cut off control which will disconnect the PV plant from the grid if it is destabilized. Destabilisation occurs when frequency or voltages gets out of limits.

4.2.3 50,2 Hertz Problem PV or Controllable Active Loads

Up to now all PV inverters were set to automatically shut down at 50,2 Hertz grid frequency. That is a slight increase of 4 ‰ to normal standard 50 Hertz. Since PV in Germany is extended up to more than 24 GW (2011) installed power the automatic shut-down of all PV system would have an enormous impact that could end in a dramatic worst case break down on the entire European integrated power grid. Since minimum load during summer time is around 70 GW, so 28.6 % of energy would instantly shut-off. In Bavaria, for example, 17 GW are installed. The new EEG maximum power output will be cut off at 70 % or the PV system must offer total re-

mote cut off if the case of too much generation occurs. Instead of cutting off PV, controllable active loads (CAL) could do balancing and use this elsewise wasted energy. At weak spots of the electrical distribution system loads can be installed which produce value which is needed when there is less energy like power-to-gas (P2G; see chapter 7.2).

4.3 Basics for Software Development

4.3.1 Methodology

The methodology contains the step by step proceedings of the program design and operation procedures. The PV battery program was designed to be with KISS approach (Keep it short and simple). Therefore Excel and the integrated Visual Basic for Applications language (VBA) were chosen as program platform. The office product is wide spread.

First approach:

- One generator profile

- One H0 load profile

- One ideal storage "bucket"

One generator (photovoltaic) supplies the consumers of a residential house in addition to the grid. The consumption of the house hold is described via a standardised load profile called H0. H0 is the only profile for residential homes. For non-residential homes there are other profiles like G0 for business, N0 for night powered heaters, L0 for farmers and A0 for Traffic lights.

The profile H0 is an average of 150 households. Time steps accuracy is 15 minutes. The interval size of 15 minutes is used as default by utilities for accounting. The PV data was obtained via SQL database of GE Global Research Europe in Garching near Munich. The one second accuracy was summed up to 15 minute means.

The load and generation profiles can be subtracted for reckoning the energy value which has to be charged or discharged (see Equation 4-7):

$$\text{Battery Energy Discharge} = \text{Load Energy General} - \text{PV Generation}$$

Equation 4-7:   *Equation for Battery Energy Discharge*

The battery calculation algorithm was designed next. Excess energy is stored to the battery within set boundaries. Energy is supplied by the battery as long the minimum state of charge is not reached. The internal consumption quote in the program is applies to the total load data and not to the total generation.

The first extension stepped into action soon afterwards. Three more generators and loads can be added to the calculation. Efficiency for the battery was added. Losses for charging and discharging can be set to different efficiency values.

To exchange the profiles more comfortably, instead of copy paste procedure, a macro (VBA-function) enables the user to easily do the exchange.

4.3.2 Definitions

Definitions make understanding much simpler. For example battery is often used as a synonym for a rechargeable battery. In the sub-chapters following items will be declared:

- Generators and Loads

- Internal Consumption and Self-Sustain Quote

- Battery States

Generators

Generators produce electric energy. The energy values are set in profiles. Four generators are applied as shown in Table 4-8. The generation profiles have to be in 15 minute intervals for a whole year.

Table 4-8:   *Generators for PV-Battery-Tool*

Generators
Photovoltaic (PV)
Wind
Combined Heat and Power (CHP)
GenX*

* GenX is open for a back-up generator or a self-defined generator

Loads

Loads consume electric energy. Loads are a gathering of residential appliances or high power consumers like the heat pump or an electric vehicle. The energy values are set in profiles. Four loads are applied as shown in Table 4-9. The load profiles have to be in 15 minute intervals for a whole year.

Table 4-9:   *Loads for PV-Battery-Tool*

Loads
General (entire Household)
Car
Heat Pump
LoadX*

* LoadX is an open profile for a self-definable load

Internal Consumption and Self-Sustainability Quote

The internal consumption quote used in the program is the self-sustainability quote described as SSQ. Since the system is not meant for 100% self-sustainable residential homes it is still marked as internal consumption.

Internal Consumption Quote (ICQ)

The EEG law defines the internal consumption quote as the energy used from PV by energy produced from PV. The energy used from PV is the energy produced from PV subtracted by the energy fed into grid. The internal consumption quote can be seen in following Equation 4-8:

$$ICQ = \frac{Energy\ produced\ from\ PV - Energy\ fed\ into\ Grid}{Energy\ produced\ from\ PV}$$

Equation 4-8:   *Internal Consumption Equation by EEG*

Self-Sustainability Quote (SSQ)

The EEG internal consumption equation does not describe the real ratio of the total used energy at home to the used energy from Generators. The following Equation 4-9 describes the self-sustainability grade of system.

$$SSQ = \frac{Energy\ produced\ from\ Generators - Energy\ fed\ into\ Grid}{Used\ Energy\ at\ Home}$$

Equation 4-9:   *Equation of Self-sustainability Grade based on Used Energy at Home*

ICQ describes the degree of utilisation of the generator while the SSQ describes the utilisation condition of the entire.

Examples for the ICQ and SSQ equations:

Only a small PV system with 2 kW is considered. Over a year it produced 2000 kWh. An Energy amount of 1000 kWh was supplied to the grid (fed into grid). 4000 kWh have been supplied by the grid by the energy supply company (ESC) / utility.

For Equation 4-8:

$$ICQ_{example} = \frac{2000\ kWh - 1000\ kWh}{2000\ kWh} = 50\ \%$$

For Equation 4-9 used Energy is supplied energy from ESC + (Energy produced from PV – Energy fed into Grid):

$$SSQ_{example} = \frac{2000\ kWh - 1000\ kWh}{4000\ kWh + (2000\ kWh - 1000\ kWh)} = 20\ \%$$

Equation 4-9 is the equation used in the program.

In the following charts are the characteristics of IC and SSQ shown. The chart is standardised for 10.000 kWh/a of general load, the battery capacity is zero. Figure 4-29 and Figure 4-30 shows the IC and SSQ in dependency of the PV Generator size. In the first chart PV generator size is step by step increased linearly to 20 kW power and in the second chart scaled logarithmically. Standard utilisation is one thousand hours per one kW installed power.
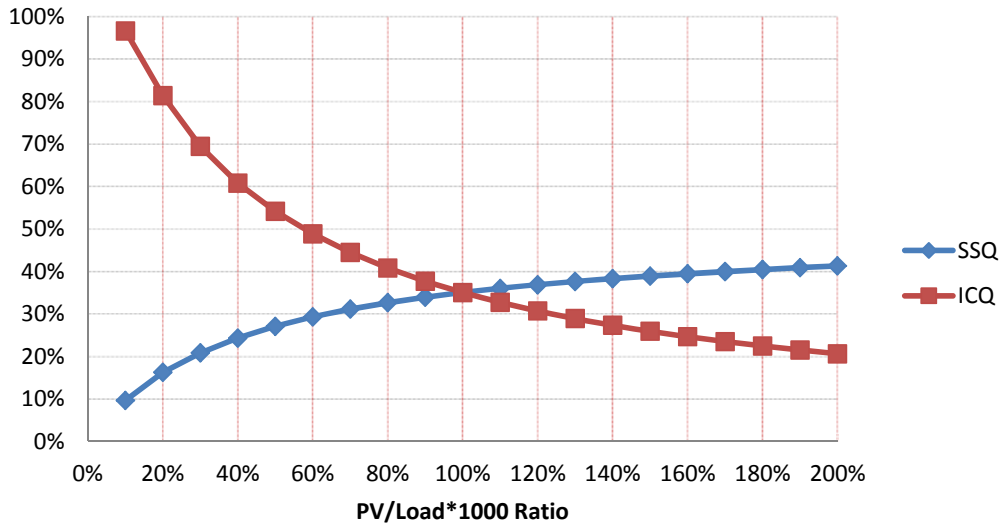
Figure 4-29: *ICQ and SSQ scaled linear to PV size multiplied by a utilization time of 1000 h divided by Load*
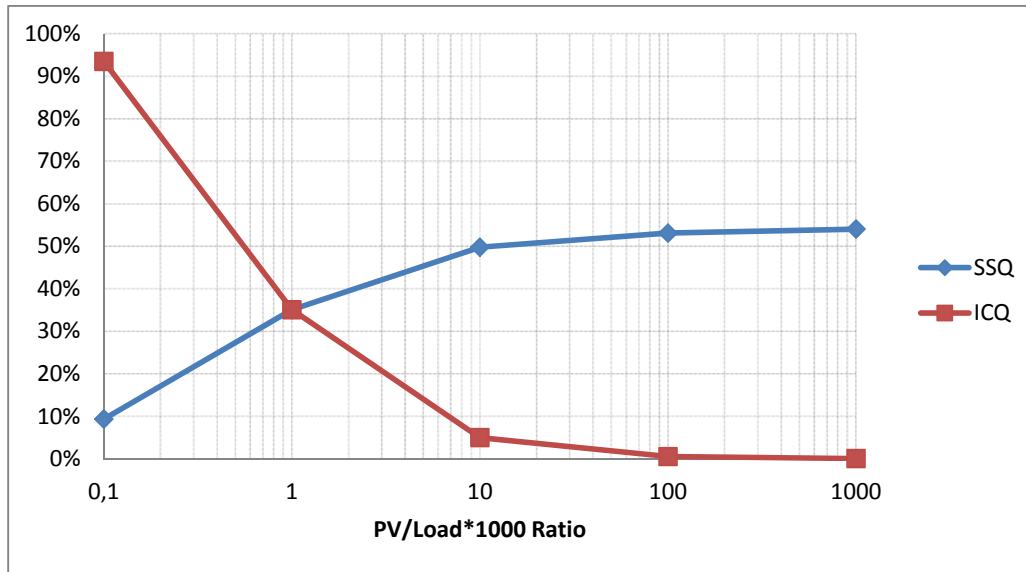
Figure 4-30: *ICQ and SSQ logarithmically scaled*

Looking at the equations for ICQ and SSQ there are three ways to improve the internal consumption quote respectively the self-sustainability grade:

1. Increase power output from generators / PV

2. Decrease energy feed into grid

3. Decrease energy use at home

These three steps refer to many possible options:

at 1.   Install a more powerful PV generator,
         a small additional generator to provide at every time of day.

at 2.   Usage of a storage,
         adjust energy consumption behaviour,
         switch loads to sun shine hours (decrease idle load)

at 3.   Buy class A to A+++* labelled equipment, pay attention to idle loads

         *EU Classes A to D see Annex page A

In this project each point is considered, but the focus will be on storage dimensioning.

Battery Load States

Battery load states define the stored energy level. There are many boundaries to describe the battery state.

SOC max and min of the battery

If the battery is fully charged the maximum state of charge (SoC) is reached and the battery is labelled full; SoC_{max} is therefore reached. If the battery is totally discharged this state is called empty also SoC_{min} with a state of available charge of zero. For maximum and minimum SoC see Figure 4-31.

SOC max of the battery and allowed minimum

Batteries are normally not allowed to discharge beyond a certain allowed minimum SoC_{min} (see Figure 4-32).
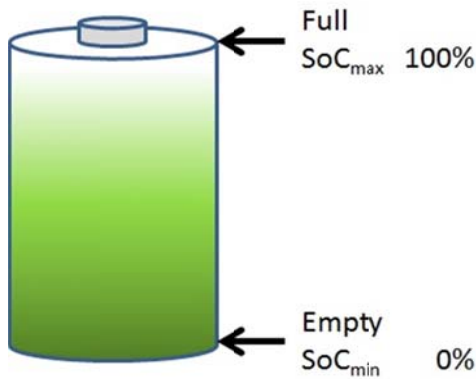
| **Figure 4-31:** | SoC Maximum and Minimum of Battery | **Figure 4-32:** | SoC Maximum of Battery and Allowed stated Minimum |
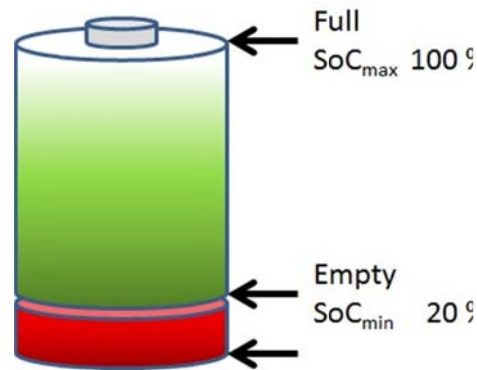
SOC allowed maximum and minimum of the battery

The maximum SoC is normally stated 100%. In many cases also a reduced charging voltage reduces stress and increases the life time of the battery. There are two possibilities shown in Figure 4-33 to define the SoC_{max} with a percentage. The maximum SoC of the battery can be defined as 100% or the allowed maximum, SoC_{max}, can be stated 100%. For the program development the figure on the right side was chosen. DoD is the contrary of SoC. While the SoC has a zero percentage charge the DoD is at its maximum and vice versa.
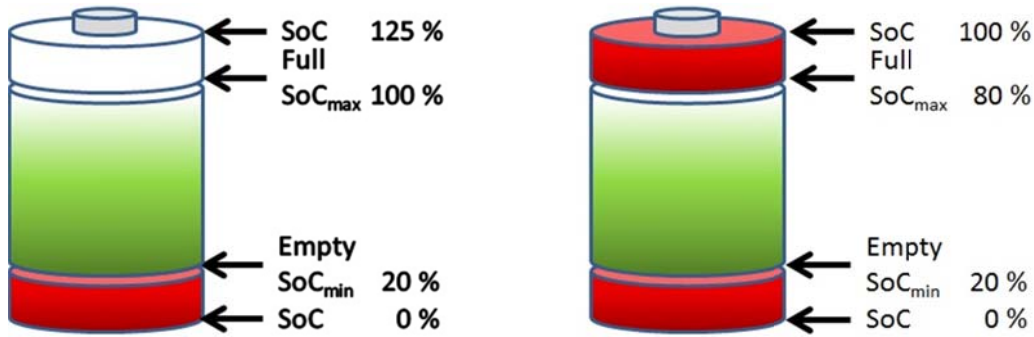
Figure 4-33:   *Allowed SoC Maximum and Minimum are stated*

Cycles per Year

Cycles per year defines the energy input to the battery without further losses divided by the useable capacity of the battery (see Equation 4-10). These cycles are full cycles. The battery is not fully charged each time during the year many. The occurrences appear in case produced energy is insufficient. These cycles are less stressful to the battery.

$$Cyles\ per\ year = \frac{Energy\ Input\ before\ Losses}{Battery\ Capacity}$$

Equation 4-10:   *Calculation Cycle Counts per Year*

System Storage Efficiency

Efficiency is the ratio of useable energy to the applied energy. In case of the battery efficiency for charging and discharging are applied (see Equation 4-11 and Equation 4-12).

$$Efficiency\ of\ Storage\ Charging = \frac{Stored\ Energy}{Input\ Energy}$$

Equation 4-11:   *Energy Efficiency of Charging the Storage*

$$Efficiency\ of\ Storage\ Discharging = \frac{Output\ Energy}{Stored\ Energy}$$

Equation 4-12:   *Energy Efficiency of Discharging the Storage*

4.3.3 Standard Households one to three

Standard Household 1

Standard household 0 is a household with four persons. Detailed information is found on the list:

- ~ 4 people

- ~ 5000 kWh General Load

- 5 kW roof-top-installation

Ratio of loads: General 100 %.

Standard Household 2

Standard household 2 is a household with four persons and with a view to the future with two electric powered or hybrid plug in cars.

- All features of Household 1 in addition or exchange with:

- 10 kW roof-top-installation
  Dimension factor for PV will rise   due to cost drop for modules prise rise in power cost cutting of subsidies

- 5000 kWh for two electric powered vehicles: one plug in hybrid and one EV or two plug in hybrids. Demand estimated 25.000 km/a for both cars in total. electric energy for 100 km: ~ 20 kWh $\Rightarrow 20\ \frac{kWh}{100\ km} \times 250\ \frac{100\ km}{a} = 5000\ \frac{kWh}{a}$

Ratio of loads: General 50 %, Car 50 %

Standard Household 3

Standard household 3 is a household with four persons, owning two electric powered or hybrid plug in cars and the house is supplied by a warmth pump.

- All features of Household 2 in addition or exchange with:

- 15 kW roof-top-installation   Dimension factor for PV will rise due to cost drop for modules prise rise in power cost   cutting of subsidies

- 5000 kWh for Heat Pump

Ratio of loads: General 33,33 %, Car 33,33 %, Heat Pump 33,33 %

4.4 Design-Tool for Capacity Dimensioning General

Program features-list:

- 15 Minute Time Steps
- 4 Load and Generators Profiles each
- Easy Exchange of Profiles
- Profile Example view
- Robustness Simulation
- Monte Carlo Simulation

The Simulation Tool is parted in single tabs:

(1) Main Menu

(2) Profile Overview

(3) Parameter Settings

(4) One Year Data Calculation

(5) Monte Carlo Simulation

(6) Robustness Analysis

For each menu a sub-chapter can be found below.

At the bottom of the Excel screen the tab-bar can be found:

The program is structured in six tabs. The following Table 4-10 shows all tabs with a picture.

Table 4-10: *The six Program Tabs*

(1) Main Menu

(2) Profile Overview

(3) Parameter Settings

(4) One Year Data Calculation

(5) Monte Carlo Simulation

(6) Robustness Analysis

4.4.1 Main Menu

The main menu offers every main entry parameter for generators, loads and battery as well as important output values like energy feed into grid, energy obtained from ESC and battery characteristics (see Figure 4-34). Generation, Load and Battery size are editable. After entering data to the INPUT section - headings marked in light blue - by pressing the Calculate button on the right sight OUTPUT data, the monthly view chart as well as the two days example chart will be updated immediately. For an even more detailed analysis click "Goto Monte Carlo Simulation" next to the "Calculate" button.

The main menu supports the three sections:

- Input
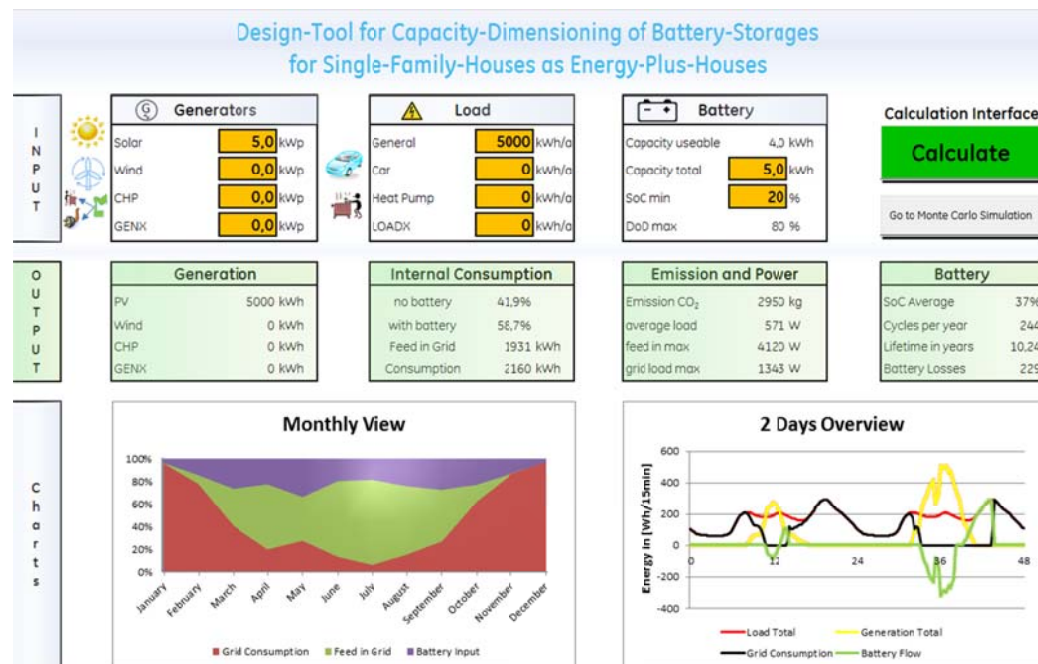
- Output

- Charts

Figure 4-34: Main Menu Tab: Input, Output, Charts and Calculation Interface

Interface

Calculation Interface

The Calculate button will change colour if an   in-put value is changed.

■ Red – not yet calculated

■ Green – calculated

For a more detailed simulation press the Monte Carlo Simulation button. More information you will find in chapter 4.4.5.

Easy Exchange Interface

The button "Exchange Profile" will replace any profile easily. Via the drop-down menu the profile to exchange can be chosen. The specific folder will open and a selectable list of profile will be shown.

The profile file consists out of the heading and 35040 rows of data. The profile needs to have 15 minute average values and start with first of January 00:00 and end on December the 31st 23:45. In Table 4-11 an example is shown of how the *.xlsx file (Windows Update adds compatibility for EXCEL 2003 Version) have to look like:
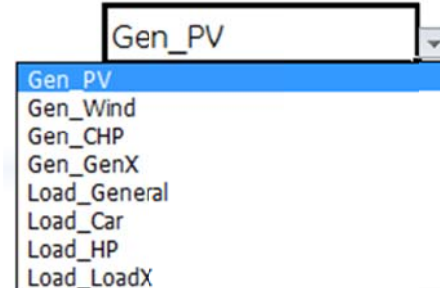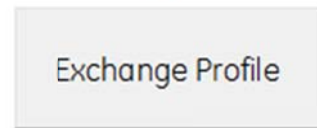
Table 4-11: *Example cut-out Profile Table*

Time	Value
01.01. 00:00	123
01.01. 00:15	234
⋮	⋮
31.12. 23:45	345

Input

Generation

Values for Rated Power in kW for generators:

- Solar

- Wind

- Combined Heat and Power (CHP)

- GENX *

ⓖ	Generators	
Solar	5,0	kWp
Wind	0,0	kWp
CHP	0,0	kWp
GENX	0,0	kWp

* GenX is open for a back-up generator or a self-defined generator.

Load

The load box preserves data in energy per year for following consumer:

- General

- Car

- Heat pump

- LOADX *

⚠	Load	
General	5000	kWh/a
Car	0	kWh/a
Heat Pump	0	kWh/a
LOADX	0	kWh/a

* LoadX is an open profile for a self-definable load.

Battery

The battery box allows entering following battery parameters:

- Total Capacity

- Minimum allowed State of Charge (SoC$_{min}$)

Useable Capacity will then be calculated.

🔋	Battery	
Capacity useable		4,0 kWh
Capacity total	5,0	kWh
SoC min	20	%
DoD max		80 %

The battery parameter for the upper bound can be changed in the parameter settings (see chapter 4.4.3 "Parameter Settings").

Output

Generation

Due to the kWp normed profiles the generation profiles are multiplied by the rated Power. PV also takes usage hours into account:

$$Factor = \frac{P\ (radted\ Power) \times t\ (in\ hours)}{1000\ kWh}$$

An Example:

Pr = 5 kW

t = 942 h (Berlin)

$$Factor = \frac{5\ kWp \times 942\ h}{1000\ kWh} = 4.706 \Rightarrow$$

Energy Generation per year: 4706 kWh

Generation	
PV	4706 kWh
Wind	0 kWh
CHP	0 kWh
GENX	0 kWh

Internal Consumption Quote (ICQ)

This Area shows the ICQ without and with an installed battery system. Also the grid consumption and feed into grid energy is shown.

Attention:
The ICQ used in the program is the SSQ defined in chapter 4.3.2.

Internal Consumption	
no battery	41,7%
with battery	58,3%
Feed in Grid	1703 kWh
Consumption	1895 kWh

Emission and Power (EP)

The EP field supports data to saved CO_2 emissions, if all sources are stated renewable. The factor therefore is 590 kg per MWh. In addition the maximum feed in grid and grid load is added.

Emission and Power	
Emission CO_2	2777 kg
average load	542 W
feed in max	3873 W
grid load max	1276 W

Battery

State of charge (SoC) shows the average charge status over the whole year, which can be an identifier for a significantly reduction of battery life time. E.g.: an average over 85 % is bad for storage reasons (see chapter 3.2.2).

Battery	
SoC Average	42%
Cycles per year	255
Lifetime in years	9,80
Battery Losses	148

Lifetime in years is based on full cycles.

$$Lifetime = \frac{Total\ amout\ of\ achivable\ Cycles\ (see\ battery\ data-sheet)}{Cycles\ per\ year}$$

Charts

In Figure 4-35 a monthly chart shows the energy sum of each month for

- Energy from ESC
- Feed into Grid
- Battery Input

Feed into grid rises till July, green line, while grid consumption is contrary and rises in winter months; the battery throughput depends on the battery capacity. From March to September the battery input is almost identical. The capacity could be increased for higher internal consumption quotes since feed into grid is sufficient and energy has still to be supplied from ESC. Battery input hits its maxima around March and September, due to moderate irradiation and moderate energy demand. In summer the energy input is lower. There is much excess energy and demand is at its minimum. The battery is probably not even discharged during the night. For that reason the grid consumption hits also a minimum. The battery is not efficiently used between the months October with February. At this time, for better battery life expectancy the charge algorithm should be optimized for a higher average state of charge.

	January	February	March	April	May	June	July	August	September	October	November	December
Energy from ESC	304	194	128	77	97	89	71	77	133	188	271	301
Feed into Grid	2	31	153	303	113	344	441	271	157	59	4	0
Battery Input	45	86	148	148	152	128	154	150	139	106	71	44

Figure 4-35: *Monthly chart: Energy supply by ESC, feed into grid and battery input*

The following Figure 4-36 shows the ratio between the three energy sums in every month as 100 % in an accumulated view. Example July (data obtained from chart; see Figure 4-35):

$Energy\ Supply\ from\ ESC = 71\ kWh$ $\quad\quad Sum = 71 + 441 + 51 = 563\ kWh$

$Feed\ into\ Grid = 441\ kWh$ $\quad\quad \Rightarrow ESC = \frac{71}{563} = 12.6\ \%$

$Battery\ Input = 51\ kWh$ $\quad\quad \Rightarrow Feed\ into\ grid = \frac{441}{563} = 78.3\ \%$

$$\Rightarrow Battery\ Input = \frac{51}{563} = 9.1\ \%$$
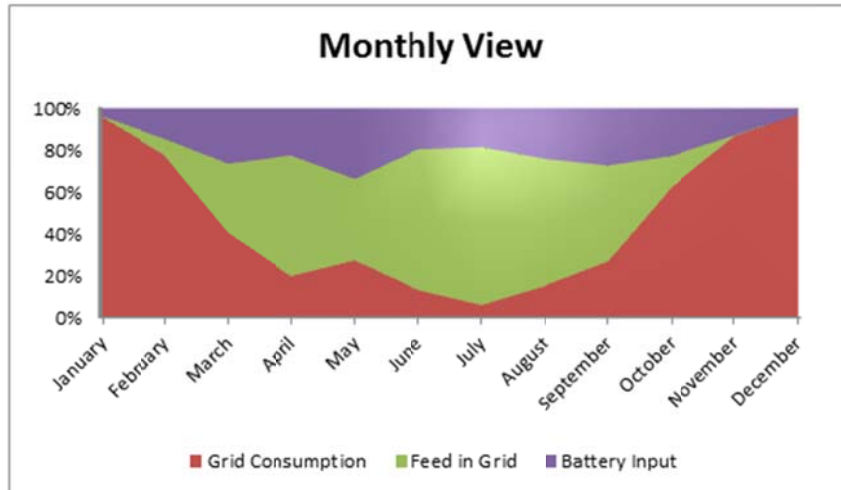
Figure 4-36: *Grid Consumption, Feed in Grid and Battery Input summed up every Month as 100 % and set into ratio*

The two day overview is an example of data in February (see Figure 4-37). The chart shows generation (yellow), battery in and output (green) under the defined efficiencies, grid consumption (black) and the current load (red). All data are directly calculation values and therefore in watt hours per 15 min Intervals. The average power is extracted by multiplying the energy values by factor four Watt per Wh/15min.
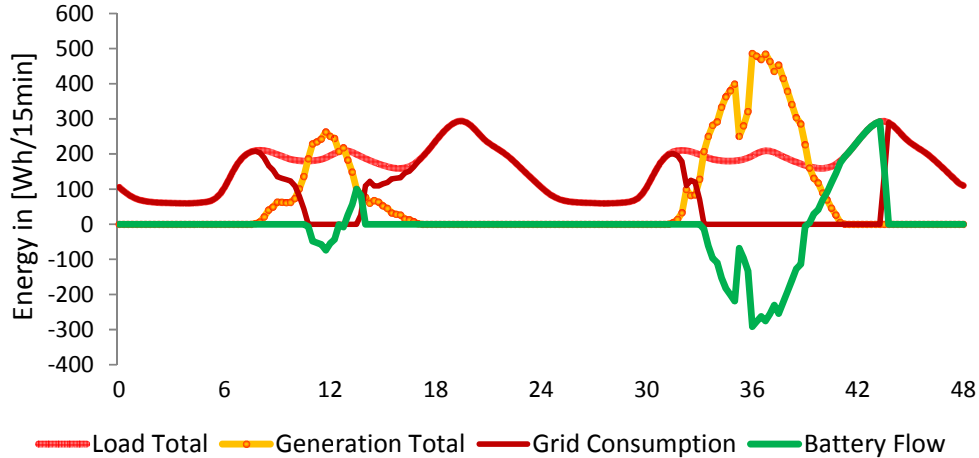
Figure 4-37: *Two days overview of the energy balancing of PV Battery system*

4.4.2 Profile Overview

The profile overview enables the view to the different profiles. The profiles can be shown in detail by disabling the other graphs by clicking the buttons shown in Figure 4-38. The load and generation graph has an all on/off button each to show or hide

all loads / generations and enable the user to quickly display one graph again by activating it.
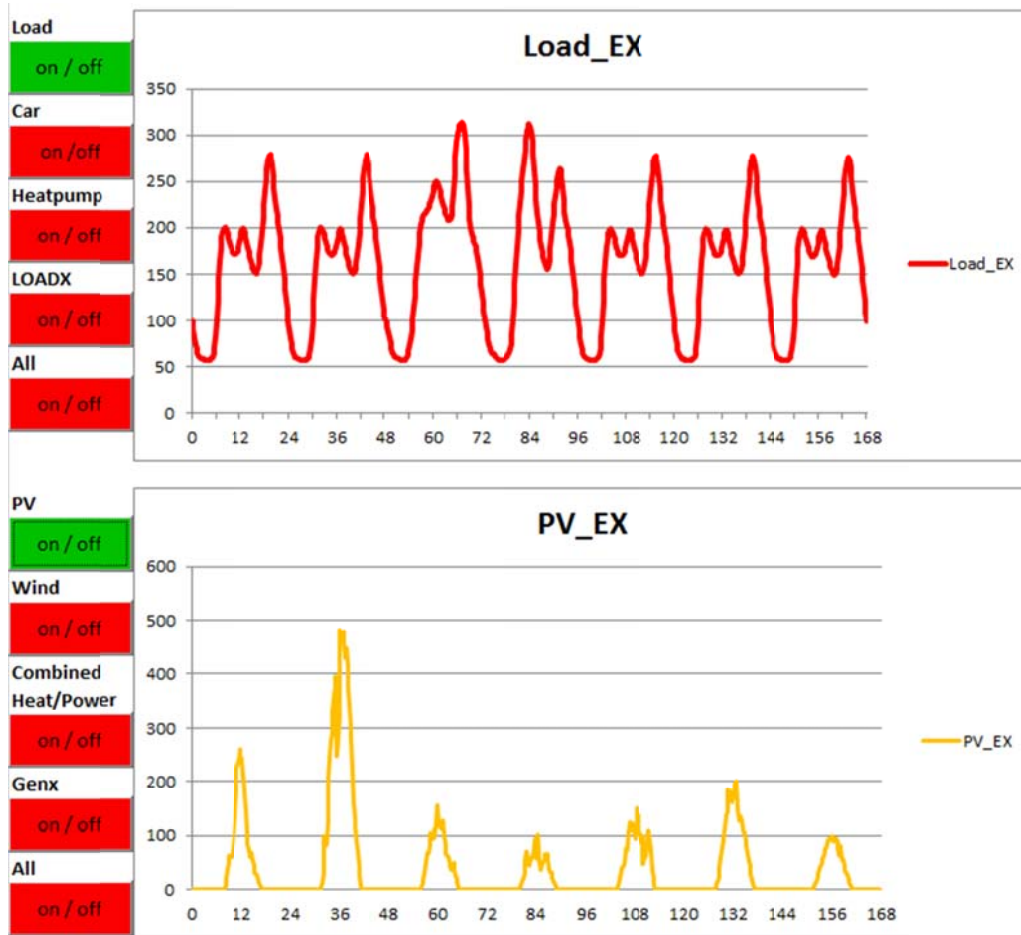
Figure 4-38   *Profile overview example of loads (first chart) and PV generation chart (second chart)*

4.4.3 Parameter Settings

The parameter settings tab give you the total overview of enabled and used parameters (see Figure 4-39). Data from the main menu is marked blue. The advanced settings are marked orange. A list of the editable parameters and reasonable range values can be found in Table 4-12. Generation and battery data can be edited in more detail. The blue marked fields are a copy from the main menu to give an overview of all parameters in one tab. The blue fields will be overwritten if changed in the parameter settings tab. Orange labelled fields can be edited, not filled cells are open for further implementation

Table 4-12:   *Parameter and Reasonable Range Values*

Parameter	Reasonable Range
70% PV cut off	On / Off
PV – Hours	700 … 2000
PV to Inverter Ratio	0.9 to 2, 3 …
Batter – Lifetime Cycles	800 … 7000
Battery – average Input / Output Efficiency	0.8 … 0.99
Battery – Maximum Charge Level (SoC$_{max}$)	0.8 … 1.0

Figure 4-39:   *Parameter Settings Tab: Blue fields, copy of main menu. Orange labelled fields are additional parameters*

4.4.4 One Year Data Calculation

The one year data calculation tab contains all necessary calculations and data for a one year simulation. The display shows sums of all energy values and the multiplication factors. The first column supplies the time information in the format DD.MM.YYYY and time hh:mm. D stands for day, M for Month, Y for Year, h for hour and m for minute. The calculation columns are marked with orange front colour on grey back colour. The Indexes in the one year data calculation tab are found in Table 4-13.

Table 4-13:   *Indexes used in the in One Year Data Calculation*

Index	Explanation
E	Energy
0	Standard Profile
X	Standard Profile Multiplied by factor X
Inc	Inclusive
-	Consumed from
+/-	Feed in / consumed from

Load data for the four different loads are contained in columns B to I. Column B contains the standardised profile LoadE0, while column C contains the multiplication with the Load-multiplication factor. Generation data for the four generators are contained in columns J to Q. The sum of all loads per 15 min interval is found in column R. The sum of all generation per 15 min interval is found in column S. The value for load subtracted by generation is the basis for the battery charging calculation (column T). Column U contains the state of charge energy of the usable capacity in [Wh]. Columns V to X contain battery characteristics. Columns Z to AB contains the energy supplied via the distribution grid and energy feed into grid. Column AC contains the SoC value of the total battery capacity. The simulation requires 15 minute interval averages on Energy in Wh, resulting in a 35040 rows of data for one year. Load Profiles have to be normed to 1000 kWh per year. Generation Profiles are normed to their full time usage hours or to general 1000 kWh per year. In Figure 4-40 a basic overview of the one year data calculation is shown. The basic view features a minimisation of loads and generation to the general residential load (Load_EX) and a photovoltaic system (PV_EX). The battery columns were reduced to the important columns without any battery losses.

Figure 4-40 One Year Data Calculation Sheet containing basic view of Loads, Generators, SoC of the Battery and Grid data

4.4.5 Monte Carlo Simulation

The Monte Carlo Simulation (MCS) gives the opportunity to see what bandwidth variety the conclusion can have. The MCS calculate the data by diversifying the loads, generations and battery-sizes. Therefore the loads and generations are changed from plus minus X % with a Gauss-distribution in eleven quantified steps. The battery values are distributed as a Weibull-distribution, due to the fact that batteries mostly do not hit their rated capacity. Also they are affected over time by their usage, which will lead to capacity loss. As conclusion a bandwidth variety with their possibilities of occurrence are given. The parameter can be set.
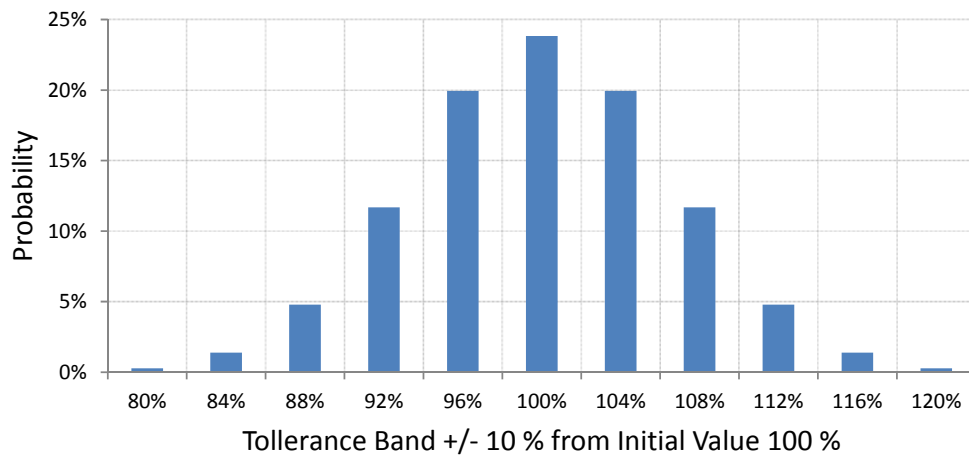
Figure 4-41:   *Gauss-Distribution*
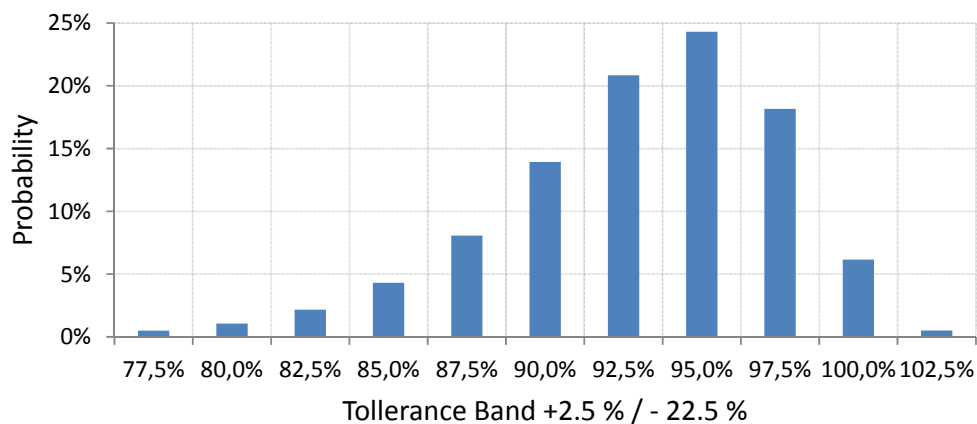
Figure 4-42:   *Weibull-Distribution*

Plot for Standard Values: PV 5 kW, Load General 5000 kWh/h, Battery 5 kWh, SoC 20%, Maximum Load
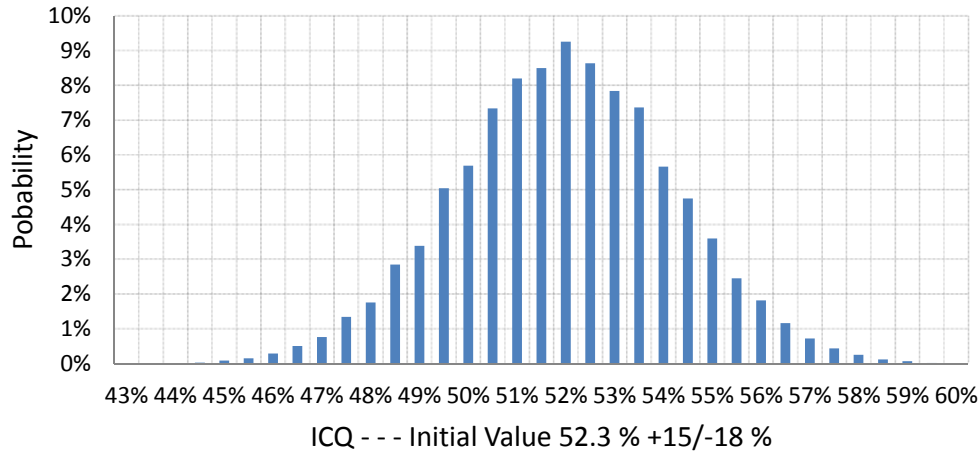
Figure 4-43: *Bandwidth – Probability over Internal Consumption Quote*

4.4.6 Robustness Simulation

The robustness simulation is like the MCS an analysis type where more information can be gathered. For robustness simulation ratios are taken into account. There are two ratios: PV to Load and Battery to Load ratio (see Table 4-14). Every output parameter can be displayed as dependency of the ratios which maxes similar sized systems comparable.

Table 4-14: *Ratios for Robustness Simulation*

Ratio #	Ratio between … and …	Ratio Calculation
1 PV	Generation PV and Load	$0.1 \dots 2 \frac{kW}{1000\ kWh}$
2 Bat	Battery and Load	$0.1 \dots 20 \frac{kWh}{1000\ kWh}$

Example:

Generation PV and Load Ratio = 1 (Ratio #1 PV)

$Load := 5000\ kWh$

$$\Rightarrow PV \quad = Load \times (Ratio\ \#1\ PV) = 5000\ kWh \times 1\ \frac{kW}{1000\ kWh} =$$

$$= 5\ kW$$

Battery and Load = 2 (Ratio #2 Bat)

$$\Rightarrow Battery = Load \times (Ratio\ \#1\ Bat) = 5000\ k\cancel{W}h \times 2\ \frac{kWh}{1000\ k\cancel{W}h} = \frac{2 \times 5\cancel{000}\ kWh}{1\cancel{000}} =$$

$$= 10\ kWh$$

Similar Systems:

If ratios and additional background parameters (see 4.4.3) stay the same technical output values stay the same; economical costs vary.

The results of the robustness simulation are shown in chapter 5.

4.5 Calculation for PV-Battery Tool

4.5.1 Calculation General

Calculation for PV-Battery-Tool elucidated the features implemented of Excel and the visual basic for application language (VBA). The calculation in Excel is done via formula written to cells (see Figure 4-44). Another way to execute function is by Macros. Macros can perform more complex functions. Macros can call automatically achieve tasks also doable by hand, but are much faster by using Macros (see Figure 4-45).

Figure 4-44: *Formula in Cell A4 calculates the sum of A1 + A2 + A3 = 71 + 441 + 51 = 563*

```
Option Explicit

Sub BasicExampleAdd()

    Dim Sum As Integer
    Sum = Range("A1").Value _
                    + Cells(2, 1).Value _
                    + Cells(3, 1).Value
    Range("A4").Value = Sum

End Sub
```

Figure 4-45: *Mini Excel Macro: Sum up 3 values (A1, Cell 2,1 and Cell 3,1) and write them to cell A4. Cell 2,1 is A2 and Cell 3,1 is A3*

4.5.2 Excel Macros

Macros are the functions of VBA, which can be executed by Excel. Macros can be called by buttons, a worksheet change and directly by visual basics. Macros make recurring sequences of work easier and much faster. The user-interface of VBA is shown in Figure 4-46.

Example Macro DevResetSheetInitialCond() (see Figure 4-47) resets the input and price data to initial values and calculates the output values. The call Calc_Click calls the function for calculation the simulation. The green lines are comments which will not be executed.
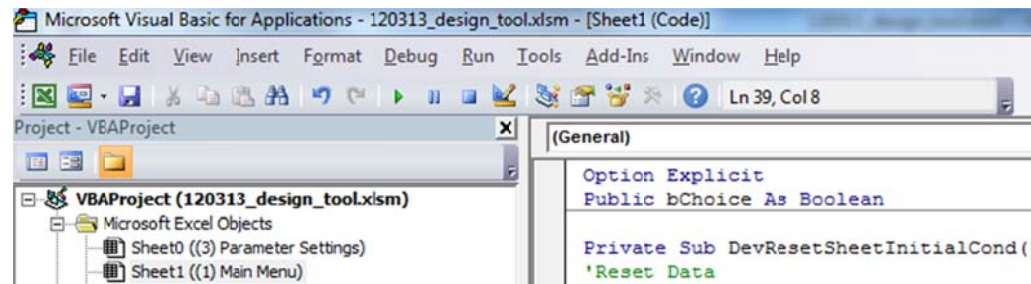
Figure 4-46:   *VBA Interface: toolbar, project and editor window.*

```
Option Explicit

Private Sub DevResetSheetInitialCond()
'Reset Data

    With Sheet1

        'Reset Input Generators
            .Range("gen_pv").Value = 5
            .Range("gen_wind").Value = 0
            .Range("gen_chp").Value = 0
            .Range("gen_genx").Value = 0

        'Reset Input Loads
            .Range("load_load").Value = 5000
            .Range("load_heatpump").Value = 0
            .Range("load_car").Value = 0
            .Range("load_loadx").Value = 0

        'Reset Input Battery Data
            .Range("bat_cap_total").Value = 15
            .Range("bat_soc").Value = 20

        'Reset Costs
            .Range("cost_pv").Value = 2000
            .Range("cost_wind").Value = 1500|
            .Range("cost_chp").Value = 2000
            .Range("cost_genx").Value = ""

        'Rest Price Data
            .Range("price_Bat").Value = 1000
            .Range("price_ESC").Value = 0.2443

    End With

    'Recalculate Values
    Call Calc_Click

End Sub 'Reset done. Values Calculated
```

Figure 4-47: *Example Macro: DevResetSheetInitialCond() resets the input and price data to initial values and calculates the output values.*

Profiles normed (Loads)

The Load profiles are normed to 1000 kWh per year.

The Energy demand x for one time step is calculated by the x kWh/a entered in the Load profile window. Factor R stands for Recalculate or Resize.

$$\bar{E}_{demand\ x} = \underbrace{\frac{x\ in\ [kWh/a]}{1000\ kWh/a}}_{\text{Factor R}} \times \bar{E}_{demand\ 0}$$

Equation 4-13: *Calculation of Energy Consumption*

The general load profile is an average of 150 Single-Households normed to 1000 kWh/a.

Resize Calculation Example:

Time   January 1st 00:00

General Energy Demand x   5000 kWh/a

Profile Energy Value   27 Wh (in this 15 min time step)
                                   Power:

$$P = 27\ Wh\ \times\ \frac{60\ \frac{min}{h}}{15\ min} = 27\ Wh \times \frac{4}{h} = 108\ W$$

⇨ Factor

⇨ $\bar{E}_{demand\ x}$

$$R = \frac{x\ in\ [kWh/a]}{1000\ kWh/a} = \frac{5000\ kWh/a}{1000\ kWh/a} = 5$$
$$\bar{E}_{demand\ x} = R \times 27\ Wh = 5 \times 27\ Wh = 135\ Wh$$

Profiles normed to 1 kW (Generators)

Generation profiles are normed to 1 kW of generator power; except PV; PV is normed to 1000 kWh/a. The PV full time usage hours for the year can be edited in the parameter settings tab. As well the PV to Inverter Ratio can be edited to limit PV generation output.

Battery Algorithm

The battery algorithm is shown by the three sequence charts. The battery system recalls generation and load data (see Figure 4-48). In case generation exceeds the consumption energy the battery switch to the battery charging algorithm, else the battery is discharged. In case load energy is equal to the generation energy the charge algorithm is applied.
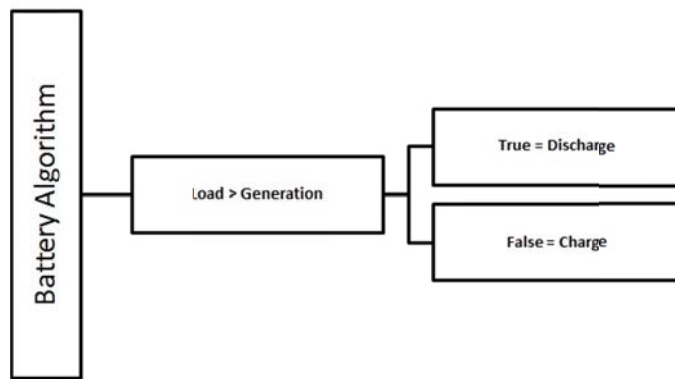
Figure 4-48: Battery Algorithm to switch to Charge or Discharge Algorithm

Battery Charging Algorithm

In case the battery enters the charging algorithm the next step is to recall the actual SoC. If SoC is bigger or equal to the maximum SoC the program checks if the maximum SoC would be exceeded. If so the battery is not charged to the maximum SoC limit. The surplus is fed into the grid. If the last SoC is the maximum SoC all energy is fed into the grid (see Figure 4-49).
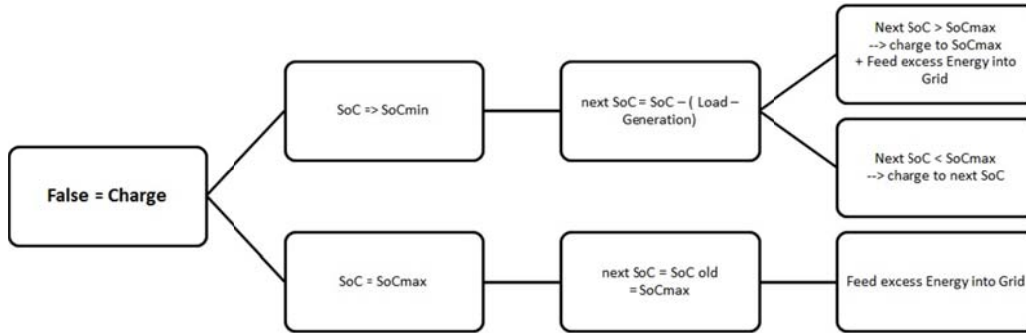
Figure 4-49:   *Battery Charging Algorithm; the steps are checked from right to left*

Battery Discharging Algorithm

The battery discharging algorithm recalls the SoC first. The next step in case of the SoC is lower or equal full capacity but not minimum SoC the battery is discharged. If the minimum SoC would be underrun, the battery is only discharged to the minimum SoC. The remaining demand for powering the loads is withdrawn from the power grid. If the SoC is already the minimum SoC the entire demand is powered by the grid (see Figure 4-50).
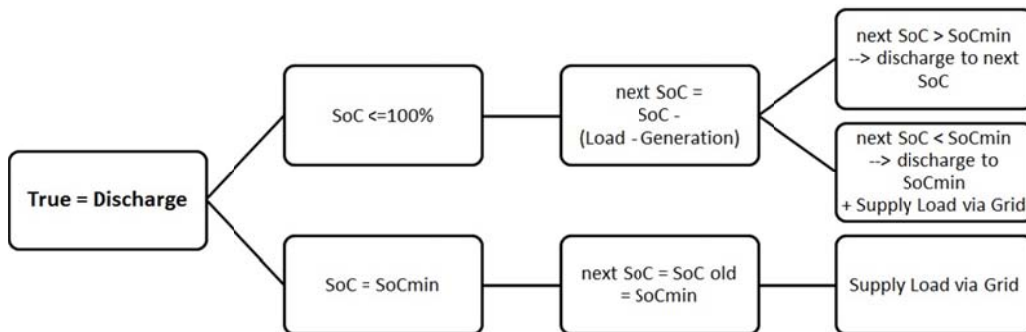
Figure 4-50:   *Battery Discharging Algorithm; the steps are checked from right to left*

PV Inverter Ratio and 70 % Cut Off

The PV inverter ratio and the 70 % cut off are directly implemented to the PV profile (e.g. see Figure 4-51). The 70 % cut off is equivalent of an inverter ratio of one divided by 0.7 resulting in a factor of 1.43. Modern PV plants will have a ratio of 1.4 or higher depending on PV module price and utilisation of the exceeding energy.
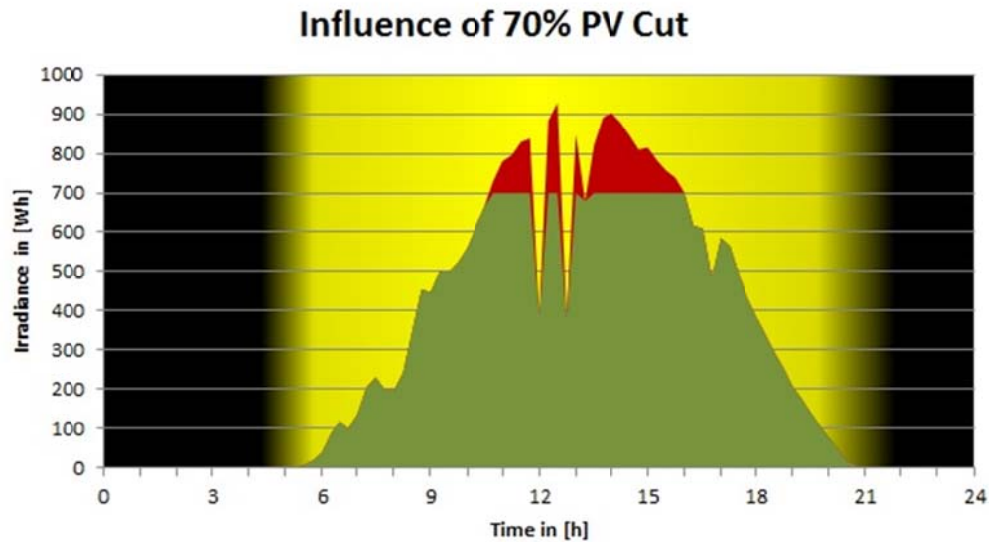
Figure 4-51: *70 % impacts on energy output of PV generator*

5 Software Development Method

5.1 Program Analysis and Finding Best Parameters

Several simulations were run with different load distributions. For running the simulation the standard generator is PV. In chapter 4.3.3 standard households were defined. For a better compatibility only the ratios were taken into account of the robustness simulation (see chapter 4.4.6). The ratios enable the comparison to similar sized systems.

5.1.1 Robustness Simulation

The following diagrams make clear how the internal consumption can be increased. The ratio PV/Load and Battery/Load have to be increased. PV or battery capacity has to be raised or load has to be decreased. The internal consumption and battery lifetime is dependent on the generation and load profiles.

Standard Household 1 features mostly daily concentrated loads during the day and at night no big idle consumers are connected to the system.

Standard Household 2 instead has got electric vehicles, which consumes as much power is the general household load.

Standard Household 3 got a heat pump and electric vehicles which could be enabled during daytime, but the tariff from the energy supply company allows a special contract to just use the heat pump during night hours.

Each standard household is the used data and profile given. The heat pump of "Standard Household 3" the heat pump operation algorithm can be improved by using the heat pump on days with high solar irradiance and other occasions which fit the energy supply company needs. The internal consumption quote rises when generation and load appear simultaneously. The battery is less used and lifetime is increased. If load and generation do not happen simultaneously the battery is able to store the energy and supply it when the generator cannot supply energy. Thus battery is used often and its lifetime decreases. This case applies for PV. The generator only produces power during daytime. Loads which are demanded during night hours cannot be supplied instantly. For each standard household two graphs are shown as well as the used profiles names. Table 5-15 shows the Inputs and the assigned pro-

files or data. The profile for load general is my own profile from the first three month of 2012 put together four times for a whole year.

Table 5-15:   *Inputs and Profile Assignment for Standard Household 1, 2 and 3*

Input	Profile / Data
Generator PV	PV_Garching_1000kWh
Load General	Rics_Loadprofile_MiddleOfJanuaryToMiddleOfMarch
Load Heat Pump	HP_night_Optimized_0_to_6
Load Car	Car_night_0_to_6_1000kWh_per_year
PV	70 % cut off: No PV/Inverter Ratio: 1
Battery	SoC_{min}: 0 % SoC_{max}: 100 % Cyclestability: 2500 Input/Output Efficiency: 98 %
Ratios #1 PV	$0.1 \ldots 2 \frac{kWp}{1000\,kWh}$
Ratio #2 Bat	$0.1 \ldots 4 \frac{kWh}{1000\,kWh}$

Chart Interpretation General

The first table shows the lifetime expectation for the battery (see Figure 5-52). The red area shows insufficient battery lifetime, the blue to dark blue area sufficient lifetime up to 20 years and the white area the lifetime between shows the area of medium lifetime expectation. The second table in the sub-chapters named Household 1 to 3 always shows the internal consumption quote over the two ratios (see Figure 5-53). The green area shows the highest, yellow medium and red low internal consumption rates. For a quick comparison the two charts are simplified using less data and compared in chapter 5.1.2.
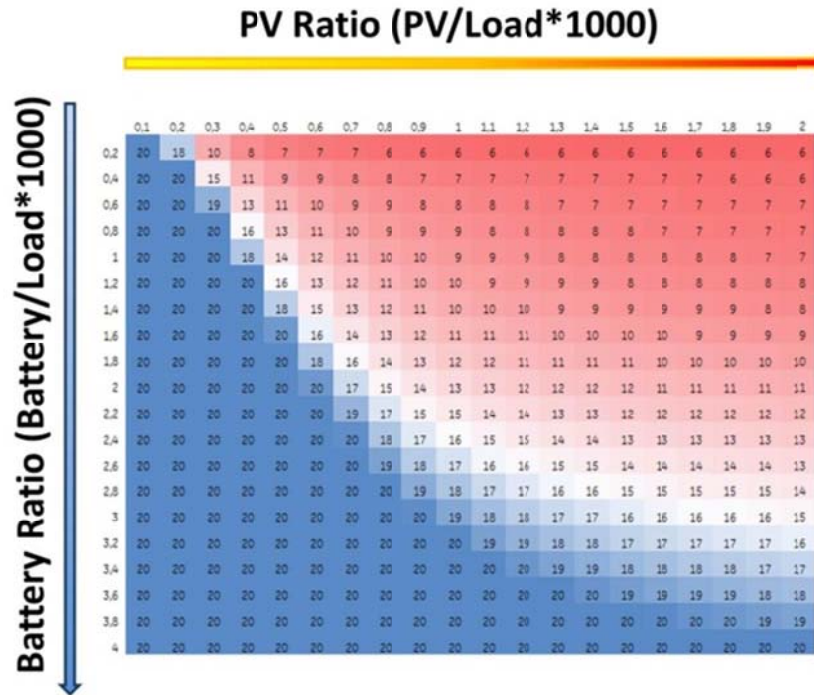
Figure 5-52: *Lifetime expectation over Battery Ratio and PV Ratio*
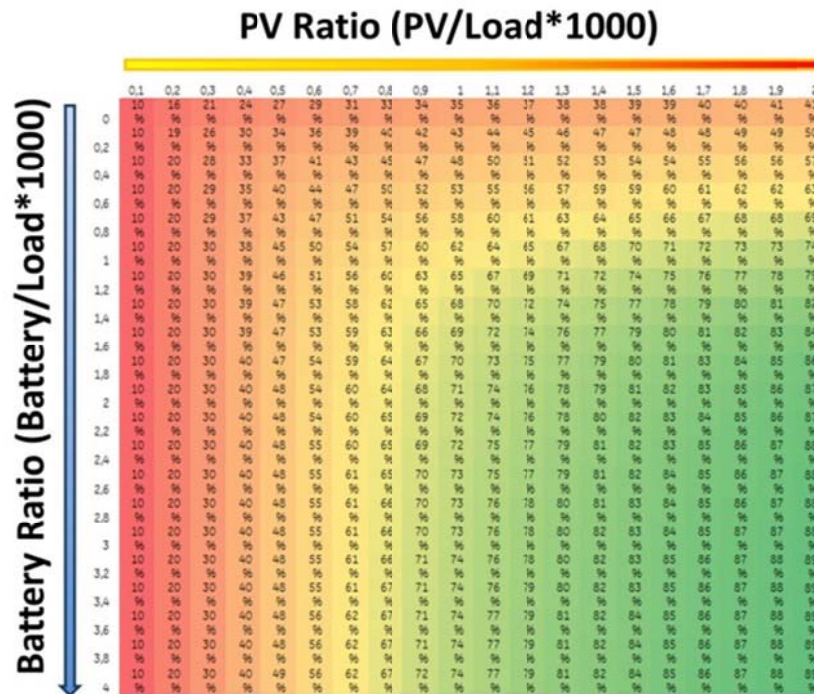
Figure 5-53: *Internal consumption Quote over Battery Ratio and PV Ratio*

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Household 1

The data for household 1 is shown in Table 5-16. The lifetime for household 1 is shown in Table 5-17**Table 5-16**. For the result for internal consumption see Table 5-18.

Table 5-16:   *Household 1 data*

Household data	Values
Persons	4
Load General	5,000 kWh
Generator PV (Ratio 1 = 1)	5 kW
Ratio PV	0.1 … 2.0 of Generator PV
Battery Capacity (Ratio 2 = 1)	5 kWh
Battery Ratio	0.2 … 4.0 of Battery Capacity 1 … 20 kWh

Table 5-17:   *Household 1 Lifetime: Low values are marked red; high values are marked dark blue; the maximum values are truncated over 20 years*

	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
0,2	20	18	10	8	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6	6
0,4	20	20	15	11	9	9	8	8	7	7	7	7	7	7	7	7	7	6	6	6
0,6	20	20	19	13	11	10	9	9	8	8	8	8	7	7	7	7	7	7	7	7
0,8	20	20	20	16	13	11	10	9	9	9	8	8	8	8	8	7	7	7	7	7
1	20	20	20	18	14	12	11	10	10	9	9	9	8	8	8	8	8	8	7	7
1,2	20	20	20	20	16	13	12	11	10	10	9	9	9	9	8	8	8	8	8	8
1,4	20	20	20	20	18	15	13	12	11	10	10	10	9	9	9	9	9	9	8	8
1,6	20	20	20	20	20	16	14	13	12	11	11	11	10	10	10	10	9	9	9	9
1,8	20	20	20	20	20	18	16	14	13	12	12	11	11	11	11	10	10	10	10	10
2	20	20	20	20	20	20	17	15	14	13	13	12	12	12	12	11	11	11	11	11
2,2	20	20	20	20	20	20	19	17	15	15	14	14	13	13	12	12	12	12	12	12
2,4	20	20	20	20	20	20	20	18	17	16	15	15	14	14	13	13	13	13	13	13
2,6	20	20	20	20	20	20	20	19	18	17	16	16	15	15	14	14	14	14	14	13
2,8	20	20	20	20	20	20	20	20	19	18	17	17	16	16	15	15	15	15	15	14
3	20	20	20	20	20	20	20	20	20	19	18	18	17	17	16	16	16	16	16	15
3,2	20	20	20	20	20	20	20	20	20	20	19	19	18	18	17	17	17	17	17	16
3,4	20	20	20	20	20	20	20	20	20	20	20	20	19	19	18	18	18	18	17	17
3,6	20	20	20	20	20	20	20	20	20	20	20	20	20	20	19	19	19	19	18	18
3,8	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	19	19
4	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20

Table 5-18: Household 1 ICQ: Low values are marked red; high values are marked green

	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
0	10	16	21	24	27	29	31	33	34	35	36	37	38	38	39	39	40	40	41	41
0,2	10	19	26	30	34	36	39	40	42	43	44	45	46	47	47	48	48	49	49	50
0,4	10	20	28	33	37	41	43	45	47	48	50	51	52	53	54	54	55	56	56	57
0,6	10	20	29	35	40	44	47	50	52	53	55	56	57	59	59	60	61	62	62	63
0,8	10	20	29	37	43	47	51	54	56	58	60	61	63	64	65	66	67	68	68	69
1	10	20	30	38	45	50	54	57	60	62	64	65	67	68	70	71	72	73	73	74
1,2	10	20	30	39	46	51	56	60	63	65	67	69	71	72	74	75	76	77	78	79
1,4	10	20	30	39	47	53	58	62	65	68	70	72	74	75	77	78	79	80	81	82
1,6	10	20	30	39	47	53	59	63	66	69	72	74	76	77	79	80	81	82	83	84
1,8	10	20	30	40	47	54	59	64	67	70	73	75	77	79	80	81	83	84	85	86
2	10	20	30	40	48	54	60	64	68	71	74	76	78	79	81	82	83	85	86	87
2,2	10	20	30	40	48	54	60	65	69	72	74	76	78	80	82	83	84	85	86	87
2,4	10	20	30	40	48	55	60	65	69	72	75	77	79	81	82	83	85	86	87	88
2,6	10	20	30	40	48	55	61	65	70	73	75	77	79	81	82	84	85	86	87	88
2,8	10	20	30	40	48	55	61	66	70	73	76	78	80	81	83	84	85	86	87	88
3	10	20	30	40	48	55	61	66	70	73	76	78	80	82	83	84	85	87	87	88
3,2	10	20	30	40	48	55	61	66	71	74	76	78	80	82	83	85	86	87	88	89
3,4	10	20	30	40	48	55	61	67	71	74	76	79	80	82	83	85	86	87	88	89
3,6	10	20	30	40	48	56	62	67	71	74	77	79	81	82	84	85	86	87	88	89
3,8	10	20	30	40	48	56	62	67	71	74	77	79	81	82	84	85	86	87	88	89
4	10	20	30	40	49	56	62	67	72	74	77	79	81	82	84	85	86	87	88	89

Household 2

The data for household 2 is shown in Table 5-19. The lifetime for household 2 is shown in Table 5-20. For the result for internal consumption see Table 5-21.

Table 5-19: Household 2 data

Household data	Values
Persons	4
Load General	5,000 kWh
Load Car	5,000 kWh
Load Total	10,000 kWh
Generator PV (Ratio 1 = 1)	10 kW
Ratio PV	0.1 … 2.0 of Generator PV 1 … 20 kW
Battery Capacity (Ratio 2 = 1)	10 kWh
Battery Ratio	0.2 … 4.0 of Battery Capacity 2 … 40 kWh

Table 5-20: Household 2 Lifetime: Low values are marked red; high values are marked dark blue; the maximum values are truncated over 20 years

	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
0,2	20	11	9	8	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6
0,4	20	16	11	9	9	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7
0,6	20	20	13	11	9	9	8	8	8	7	7	7	7	7	7	7	7	7	7	7
0,8	20	20	15	12	10	9	9	9	8	8	8	8	7	7	7	7	7	7	7	7
1	20	20	18	13	11	10	9	9	9	8	8	8	8	8	7	7	7	7	7	7
1,2	20	20	20	15	12	11	10	9	9	9	8	8	8	8	8	8	7	7	7	7
1,4	20	20	20	16	13	11	10	10	9	9	9	8	8	8	8	8	8	8	7	7
1,6	20	20	20	18	14	12	11	10	10	9	9	9	8	8	8	8	8	8	8	8
1,8	20	20	20	19	15	13	12	11	10	10	9	9	9	9	8	8	8	8	8	8
2	20	20	20	20	17	14	12	11	11	10	10	9	9	9	9	9	8	8	8	8
2,2	20	20	20	20	18	15	13	12	11	11	10	10	10	9	9	9	9	9	9	8
2,4	20	20	20	20	19	16	14	13	12	12	11	11	10	10	10	10	10	9	9	9
2,6	20	20	20	20	20	18	15	14	13	12	12	12	11	11	11	10	10	10	10	10
2,8	20	20	20	20	20	19	17	15	14	13	13	12	12	12	11	11	11	11	11	10
3	20	20	20	20	20	20	18	16	15	14	14	13	13	12	12	12	12	11	11	11
3,2	20	20	20	20	20	20	19	17	16	15	14	14	13	13	13	13	12	12	12	12
3,4	20	20	20	20	20	20	20	18	17	16	15	15	14	14	14	13	13	13	13	13
3,6	20	20	20	20	20	20	20	19	17	17	16	15	15	15	14	14	14	14	13	13
3,8	20	20	20	20	20	20	20	20	18	17	17	16	16	15	15	15	15	14	14	14
4	20	20	20	20	20	20	20	20	19	18	18	17	16	16	16	15	15	15	15	15

Table 5-21: Household 2 ICQ: Low values are marked red; high values are marked green

	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
0	8	12	15	16	18	18	19	20	20	21	21	21	22	22	22	22	23	23	23	23
0,2	10	17	20	23	24	26	27	27	28	28	29	29	29	30	30	30	30	30	31	31
0,4	10	19	24	27	29	31	32	33	34	35	35	36	36	37	37	37	37	38	38	38
0,6	10	20	26	30	33	35	37	38	39	40	41	42	42	43	43	44	44	44	45	45
0,8	10	20	28	33	37	39	41	43	44	46	47	47	48	49	49	50	50	51	51	51
1	10	20	29	35	40	43	45	47	49	50	52	53	54	54	55	56	56	57	57	58
1,2	10	20	29	36	42	46	49	51	53	55	56	57	58	59	60	61	62	63	63	64
1,4	10	20	30	38	44	48	52	55	57	59	60	62	63	64	65	66	67	68	69	69
1,6	10	20	30	38	45	50	55	58	60	63	64	66	68	69	70	71	72	73	74	75
1,8	10	20	30	39	46	52	57	61	64	66	68	70	72	73	75	76	77	78	79	80
2	10	20	30	39	47	53	59	63	66	69	71	73	75	76	78	79	80	82	83	83
2,2	10	20	30	40	48	54	59	64	67	70	73	75	77	78	80	81	82	84	85	86
2,4	10	20	30	40	48	54	60	64	68	71	73	76	78	79	81	82	83	85	86	87
2,6	10	20	30	40	48	55	60	65	69	71	74	76	78	80	81	83	84	85	86	87
2,8	10	20	30	40	48	55	61	65	69	72	74	77	79	80	82	83	84	86	87	88
3	10	20	30	40	48	55	61	66	70	72	75	77	79	81	82	84	85	86	87	88
3,2	10	20	30	40	48	55	61	66	70	73	75	78	79	81	83	84	85	86	87	88
3,4	10	20	30	40	48	55	61	66	70	73	76	78	80	81	83	84	85	86	87	88
3,6	10	20	30	40	48	56	61	66	71	73	76	78	80	82	83	85	86	87	88	89
3,8	10	20	30	40	48	56	61	67	71	74	76	78	80	82	83	85	86	87	88	89
4	10	20	30	40	48	56	62	67	71	74	76	79	80	82	84	85	86	87	88	89

Household 3

The data for household 2 is shown in Table 5-22. The lifetime for household 2 is shown in Table 5-23. For the result for internal consumption see Table 5-24.

Table 5-22:   Household 3 data

Household data	Values
Persons	4
Load General	5,000 kWh
Load Car	5,000 kWh
Load Heat Pump	5,000 kWh
Load Total	15,000 kWh
Generator PV (Ratio 1 = 1)	15 kW
Ratio PV	0.1 … 2.0 of Generator PV 1.5 … 30 kW
Battery Capacity (Ratio 2 = 1)	15 kWh
Battery Ratio	0.2 … 4.0 of Battery Capacity 3 … 60 kWh

Table 5-23:   Household 3 Lifetime: Low values are marked red; high values are marked dark blue; the maximum values are truncated over 20 years

	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
0,2	19	10	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
0,4	20	13	10	9	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7
0,6	20	16	11	10	9	8	8	8	7	7	7	7	7	7	7	7	7	7	7	7
0,8	20	20	13	11	10	9	9	8	8	8	7	7	7	7	7	7	7	7	7	7
1	20	20	15	12	10	10	9	9	8	8	8	8	7	7	7	7	7	7	7	7
1,2	20	20	17	13	11	10	9	9	9	8	8	8	8	8	7	7	7	7	7	7
1,4	20	20	19	14	12	11	10	9	9	9	8	8	8	8	8	8	8	7	7	7
1,6	20	20	20	16	13	12	11	10	10	9	9	9	8	8	8	8	8	8	8	8
1,8	20	20	20	18	14	13	11	11	10	10	9	9	9	9	9	8	8	8	8	8
2	20	20	20	19	16	14	12	12	11	11	10	10	10	9	9	9	9	9	9	9
2,2	20	20	20	20	17	15	13	12	12	11	11	11	10	10	10	10	9	9	9	9
2,4	20	20	20	20	19	16	14	13	13	12	12	11	11	11	10	10	10	10	10	10
2,6	20	20	20	20	20	17	15	14	13	13	12	12	12	11	11	11	11	10	10	10
2,8	20	20	20	20	20	18	17	15	14	14	13	13	12	12	12	12	11	11	11	11
3	20	20	20	20	20	20	18	16	15	15	14	14	13	13	13	12	12	12	12	11
3,2	20	20	20	20	20	20	19	17	16	15	15	14	14	14	13	13	13	12	12	12
3,4	20	20	20	20	20	20	20	18	17	16	16	15	15	14	14	14	13	13	13	13
3,6	20	20	20	20	20	20	20	19	18	17	17	16	16	15	15	14	14	14	14	13
3,8	20	20	20	20	20	20	20	20	19	18	17	17	16	16	16	15	15	15	14	14
4	20	20	20	20	20	20	20	20	20	19	18	18	17	17	16	16	16	15	15	15

Table 5-24: Household 3 ICQ: Low values are marked red; high values are marked green

	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7	1,8	1,9	2
0	7	10	11	12	13	13	14	14	15	15	15	15	15	15	16	16	16	16	16	16
0,2	10	15	17	19	20	21	21	22	22	22	23	23	23	23	23	23	23	23	24	24
0,4	10	17	21	24	25	26	27	28	29	29	29	30	30	30	30	30	31	31	31	31
0,6	10	19	24	27	30	31	32	33	34	35	36	36	36	37	37	37	37	38	38	38
0,8	10	20	26	31	33	35	37	38	40	40	41	42	43	43	43	44	44	44	44	45
1	10	20	28	33	37	39	41	43	44	45	46	47	48	49	49	50	50	51	51	51
1,2	10	20	29	35	40	43	45	47	49	50	51	52	53	54	55	55	56	57	57	57
1,4	10	20	29	36	42	46	48	51	53	54	56	57	58	59	60	61	61	62	62	63
1,6	10	20	30	37	43	47	51	53	55	57	59	60	61	63	63	64	65	66	67	67
1,8	10	20	30	37	44	49	52	55	58	60	61	63	64	65	66	67	68	69	70	71
2	10	20	30	38	44	49	53	56	59	61	63	65	66	67	69	70	70	71	72	73
2,2	10	20	30	38	44	50	54	58	60	62	64	66	68	69	70	71	72	73	74	75
2,4	10	20	30	38	45	50	55	58	61	63	65	67	69	70	72	73	74	75	76	77
2,6	10	20	30	38	45	50	55	59	62	64	66	68	70	71	72	74	75	76	77	78
2,8	10	20	30	38	45	51	55	59	62	64	67	68	70	72	73	75	76	77	78	79
3	10	20	30	38	45	51	56	59	62	65	67	69	71	72	74	75	76	78	79	80
3,2	10	20	30	38	45	51	56	60	63	65	67	69	71	73	74	76	77	78	79	80
3,4	10	20	30	38	45	51	56	60	63	65	68	70	71	73	75	76	77	78	79	80
3,6	10	20	30	38	45	51	56	60	63	66	68	70	72	73	75	76	77	79	80	81
3,8	10	20	30	38	46	51	56	60	63	66	68	70	72	74	75	76	78	79	80	81
4	10	20	30	38	46	52	56	60	63	66	68	70	72	74	75	77	78	79	80	81

5.1.2 Best Working Conditions

Best working conditions appear when battery lifetime and internal consumption quote gathers an optimum. Following Figure 5-54 shows a compare view of the Household charts. The first rows of internal consumption quote (ICQ) vary widely from 13 % to 41 % of one Household to another. The energy use during night is greatly increased from Household 1 over number 2 to number 3. The total energy consumption is in every case the same but the usage time differs. The internal consumption quote without battery drops dependent on the ratio of energy used during day to energy used during night the ICQ is lower for household 2 and 3 compared to household 1. For the households 1 and 2 ICQ reaches in both terms with big battery (Ratio Battery = 4) and moderate to high PV power capability (Ratio PV = 1 … 2). The lifetime for household 2 and 3 are decreased significantly. The battery should be large and the PV system should be rated to supply the energy for the whole year to satisfy consumption demand (Ratio PV = 1) to extend lifetime expectancy.

Figure 5-54: *Overview of all Households*

5.2 Economical View Today and Future

The economic costs for PV are cut every year as well as for batteries. The specific costs for PV system and for battery of today and 2015+ expectations can be found in Table 5-25. 2015+ indicates the uncertainty of the scenarios. The prices will fall to these levels between 2015 and 2020. (23) (32)

Table 5-25: *Costs for System Components: PV generator and Battery (23) (32)*

Cost for	Cost today	Cost tomorrow (2015+)
1 kW PV	2500 €	1500 €
1 kWh Battery	800 €	200 €

Calculation Procedure and Engineering Standardisation

At first the absolute costs of the systems were calculated for the years 2012 and 2015+ which is shown in the first pair of charts (see Table 5-26):

- Today Absolute Costs
- Tomorrow Absolute Costs

The following charts set costs into relation to the internal consumption quote. The charts are only dependent on the cost ratio between specific PV and battery costs

as well as on the ICQ outcomes of the households. Therefore the absolute costs were divided by the internal consumption rate. For better comparison the graphs maxima were set to 100 %. The ICQ related data can be obtained from the second pair of charts (see Table 5-27):

- Today ICQ

- Tomorrow ICQ

The charts are only dependent on the cost ratio between specific PV and battery costs as well as on the ICQ outcomes of the households. Therefore the absolute costs were divided by the internal consumption rate. For better comparison the graphs maxima were set to 100 %. All charts are taken the Ratio #1 PV and Ratio #2 Bat into account (see chapter 4.4.6). The economical interesting area of low costs for each ICQ percentage point becomes bigger if the price ratio of PV to battery is higher (battery will become cheaper faster than PV). On the following pages the first and second pair of charts can be found for household 1 to 3. Considering the money savings of the internal consumption and subsidies for PV economic benefits can be calculated to investigate the time till return of investment cost. The base should be a household which produces at least as much energy itself needs (Ratio #1 PV equals 1 or higher). Small PV System should not be coupled with a big energy storage system (PV Ratio <0.5 and Bat Ratio >3).

Table 5-26: *First pair of charts: Total Costs*

Today Absolute Costs

Ratio #1 PV

Ratio #2 Bat	10%	20%	40%	80%	100%	120%	150%	200%
0%	250	500	1000	2000	2500	3000	3750	5000
100%	1050	1300	1895	3593	4253	4872	5764	7166
200%	1850	2100	2600	4078	4873	5563	6526	8007
300%	2650	2900	3400	4400	5014	5724	6671	8124
400%	3450	3700	4200	5200	5700	6200	6950	8200

Tomorrow Absolute Costs

Ratio #1 PV

Ratio #2 Bat	10%	20%	40%	80%	100%	120%	150%	200%
0%	150	300	600	1200	1500	1800	2250	3000
100%	350	500	824	1598	1938	2268	2753	3542
200%	550	700	1000	1720	2093	2441	2944	3752
300%	750	900	1200	1800	2129	2481	2980	3781
400%	950	1100	1400	2000	2300	2600	3050	3800

Table 5-27: *Second pair of charts: ICQ*

Today ICQ

Ratio #1 PV

Ratio #2 Bat	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	84	63	42	36	32	27	21
100%	25	40	50	39	35	32	29	25
200%	14	25	39	40	37	35	32	28
300%	10	18	30	39	38	35	32	28
400%	7	14	24	33	34	33	31	28

Tomorrow ICQ

Ratio #1 PV

Ratio #2 Bat	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	84	63	42	36	32	27	21
100%	44	62	72	55	49	45	39	33
200%	28	44	61	58	53	48	43	36
300%	21	34	51	57	53	49	43	36
400%	16	28	44	52	50	47	43	36

Household 1

Table 5-28:   Household 1 Today Absolute Cost

	10%	20%	40%	80%	100%	120%	150%	200%
0%	250	500	1000	2000	2500	3000	3750	5000
100%	1050	1300	1895	3593	4253	4872	5764	7166
200%	1850	2100	2600	4078	4873	5563	6526	8007
300%	2650	2900	3400	4400	5014	5724	6671	8124
400%	3450	3700	4200	5200	5700	6200	6950	8200

Table 5-29:   Household 1 Tomorrow Absolute Cost

	10%	20%	40%	80%	100%	120%	150%	200%
0%	150	300	600	1200	1500	1800	2250	3000
100%	350	500	824	1598	1938	2268	2753	3542
200%	550	700	1000	1720	2093	2441	2944	3752
300%	750	900	1200	1800	2129	2481	2980	3781
400%	950	1100	1400	2000	2300	2600	3050	3800

Table 5-30:   Household 1 Today ICQ

	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	84	63	42	36	32	27	21
100%	25	40	50	39	35	32	29	25
200%	14	25	39	40	37	35	32	28
300%	10	18	30	39	38	35	32	28
400%	7	14	24	33	34	33	31	28

Table 5-31:   Household 1 Tomorrow ICQ

	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	84	63	42	36	32	27	21
100%	44	62	72	55	49	45	39	33
200%	28	44	61	58	53	48	43	36
300%	21	34	51	57	53	49	43	36
400%	16	28	44	52	50	47	43	36

Household 2

Table 5-32: *Household 2 Today Absolute Cost*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	250	500	1000	2000	2500	3000	3750	5000
100%	1050	1300	2212	3784	4431	5038	5903	7273
200%	1850	2100	2600	4821	5664	6409	7432	8996
300%	2650	2900	3400	5017	5906	6683	7725	9298
400%	3450	3700	4200	5200	6005	6777	7813	9365

Table 5-33: *Household 2 Tomorrow Absolute Cost*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	150	300	600	1200	1500	1800	2250	3000
100%	350	500	903	1646	1983	2310	2788	3568
200%	550	700	1000	1905	2291	2652	3171	3999
300%	750	900	1200	1954	2352	2721	3244	4075
400%	950	1100	1400	2000	2376	2744	3266	4091

Table 5-34: *Household 2 Today ICQ*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	75	50	30	25	22	18	14
100%	29	47	46	35	32	29	26	22
200%	17	29	46	39	36	34	31	27
300%	12	21	36	40	37	35	33	29
400%	9	17	29	39	38	36	33	29

Table 5-35: *Household 2 Tomorrow ICQ*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	75	50	30	25	22	18	14
100%	53	73	71	53	47	42	36	30
200%	33	52	73	61	55	51	45	38
300%	25	41	61	62	57	52	47	40
400%	19	33	52	62	57	53	47	40

Household 3

Table 5-36:   *Household 3 Today Absolute Cost*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	250	500	1000	2000	2500	3000	3750	5000
100%	1050	1300	2350	3864	4499	5095	5951	7295
200%	1850	2100	2652	4765	5539	6247	7232	8749
300%	2650	2900	3400	4954	5790	6539	7583	9206
400%	3450	3700	4200	5200	5862	6622	7688	9296

Table 5-37:   *Household 3 Tomorrow Absolute Cost*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	150	300	600	1200	1500	1800	2250	3000
100%	350	500	938	1666	2000	2324	2800	3574
200%	550	700	1013	1891	2260	2612	3121	3937
300%	750	900	1200	1938	2322	2685	3208	4052
400%	950	1100	1400	2000	2340	2706	3234	4074

Table 5-38:   *Household 3 Today ICQ*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	100	70	44	26	21	18	15	12
100%	34	54	47	36	32	30	26	22
200%	19	34	51	42	39	36	33	29
300%	14	25	40	43	40	38	35	31
400%	10	19	33	42	40	38	35	31

Table 5-39:   *Household 3 Tomorrow ICQ*

	10%	20%	40%	80%	100%	120%	150%	200%
0%	93	65	41	24	20	17	14	11
100%	57	80	71	52	46	41	35	29
200%	36	57	75	60	54	50	44	37
300%	27	44	64	61	56	52	46	39
400%	21	36	55	60	57	52	47	40

6 Program Validation

Program Validation was chosen to compare to real internal consumption quote of some residential homes. Data was obtained from a forum (photovoltaikforum.com). It is a German community was established in 2005 and discussed almost 74,000 topics and with almost 700,000 post till now (2012). Data from a battery system was not checked, there was no data available for a whole year.

6.1 Example House 1

Person 1 is further named Kai. His data of his PV system and internal consumption without battery can be found in Table 6-40.

Table 6-40:   *Kai's Household*

Data	Value
Load general	2935 kWh
Internal consumption	1214 kWh
PV generator	9,43 kW
Internal consumption quote 2010 (real)	41,4 %
ICQ (simulated	44,7 %

The program output value is 8 % higher than the measured value from Kai. With a five percentage error using only 15 minute means instead of 1 minute values an error of 2.5 % is the result. The error is dependent on user behaviour and therefore the applied profiles in the simulation.

6.2 Example House 2

Person 2 is further called Klaus. His data of his PV system and internal consumption without battery can be found in Table 6-41.

Table 6-41:   *Klaus' House*

Data	Value
Load general	2650 kWh
Internal consumption	960 kWh
PV generator	4,2 kW
PV generation	4000 kWh
Energy from ESC	1690 kWh
Internal consumption quote 2010 (real)	36,2 %
ICQ (simulated)	39,0 %

The internal consumption quote is 8 % higher than the simulated value. The total error assumes to 2.3 %. The simulation fits the output data very well.

6.3 Simulation Compare

The Saftbatterie Group quotes:

"[First simulations have shown that the addition of an energy storage capacity leads to an increased internal consumption from 30 to 35 % up to 60 to 70 %.]"

The PV-Battery-Tool calculation shows in dependency of different battery capacities an increase from 35.1 % to 74.4 % for the PV per Load * 1000 ratio equals one (see Table 6-42).

Table 6-42:   *Software Output for PV/Load * 1000 Ratio = 1*

Battery / Load * 1000	Internal Consumption Quote (PV/Load*1000=1)
0,0	**35,1%**
0,2	43,0%
0,4	48,5%
1,0	**61,8%**
2,0	71,1%
4,0	**74,4%**

7 Conclusion for Renewable Energy Balancing

In the future many options for saving energy and producing energy in an environmentally friendly way have to be taken into account as well as power grid stability.

7.1 Battery Storage

Battery storages are an important topic to answer the energy-transformation towards clean renewable energy sources. It is apparent that the European Union increases the funding of battery research and development projects every year. Battery storages are seen as one way in the future. Today batteries still have many problems (e.g. cycle stability) which will be solved or improved during further development to make batteries more cost efficient as well as lighter and smaller. The primary energy supply is divided in electrical energy and thermal energy. Therefore another way besides batteries – in also chemical methods - will lead to synthesised fuel by excess energy of the turbulent fluctuating renewable energy sources. One seminal project is the Power-to-Gas project which will be described in the following chapter 7.2. During the conversion of electric energy to fuel and vice versa enormous quantities of heat are released. Half of the year the demand for thermal energy is high. The efficiency of the process can be improved up to 80 % by using the thermal energy. Synthesised fuel can be easily transported. This advantages outways the heavy battery technology. The use of the excess energy from PV and wind is much more effective compared to the natural photosynthesis. The best storage is saving energy. The biggest potentials for energy saving in a residential home are thermal applications and disconnecting idling electronic devices from the grid. Thermal applications are the washing machine, dryer, fridge (always on), stove and oven. Electronic devices which are idling consuming are often found in the living room. Many modern television entertainment systems are connected to the internet running constantly on high power. This energy accumulates to expenses paid each year for no practically usage. Gas has the ability to store energy sessional. Batteries instead are a daily up to a maximum of weekly storage and in combination with only a PV system it has to cope with times of insufficient irradiance.

7.2 Power-to-Gas

Power-to-Gas (P2G) is also called the methanation process or photosynthesis 2.0. Methanation is the conversion from electric energy to a synthesized natural gas (methane). Carbon from carbon dioxide or carbon monoxide is converted in a chemical process with hydrogen. Hydrogen is produced using electrolyser. Electricity is supplied by wind or photovoltaic. The carbon is for example used from biogas plants. They produce not only gas but also carbon dioxide which is not yet used and nowadays released to the atmosphere. The synthetic natural gas can be transported easily via the huge gas transportation network. The P2G project is government-funded by the federal ministry of environment, nature conservation and nuclear safety. The project is a cooperation of the Centre for Solar-Energy- and Hydrogen-Research Baden-Württemberg (ZSW), Fraunhofer and Solarfuel (29). The principle of connecting the Power grid to the gas distribution network is shown in Figure 7-55. The structure is extended by a biogas power plant. The power grid and gas distribution networks are linked through gas power plants (CHP / GaS) and electrolyser and Methanation Process; Excess Energy from Wind and PV is used to supply the electric Power needed for Electrolyser and Methanation; CO_2 can be extracted from Bio Gas while it is a By-Product of Biogas; CO_2 as well as Hydrogen can be stored until it is sufficient to synthesise Methane; Methane can be stored easily contrary to electric Power; Biogas and the synthesised Gas can be supplied to homes or used in CHP or GaS; small parts of hydrogen (up to 5%) can be directly supplied to the Gas distribution Network; the heat of methanation and electrolysis processes can be used to heat the fermenter. The next steps of the project are the construction of a 250 kW production facility (2012) and an industrial sized 6 MW plant in 2013. (33)
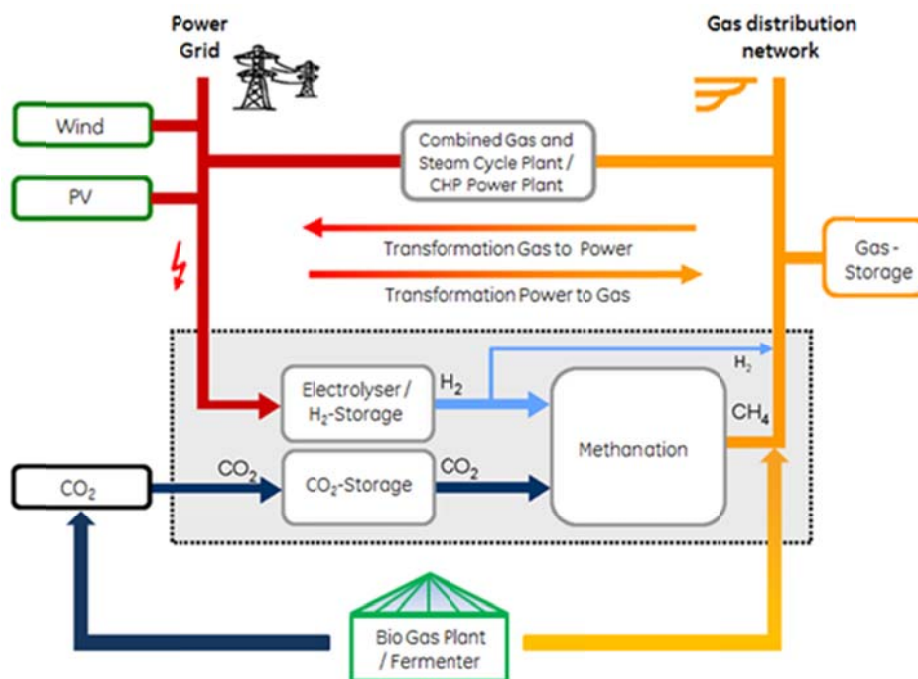
Figure 7-55: *Principle of Power-to-Gas structure extended by Biogas Plant (33)*

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Annex

EU Energy Saver Classes A to D

The EU-regulations defines several energy classes. Before 2010 there were energy classes A to G. The rating for classes is orientated on the sold consumer products. Since 2010 there are new labels and classes from A+++ to D. As an example the label of a refrigerator is shown in Figure 0-56. In future it is predicted that instead of A, A+, A++ and A+++ the number of plusses are labelled. For example 4+, 3+, ..., 0+. 4+ equals A++++ and 0+ equals A. A energy efficiency comparison of A to A+++ for refrigerators is looked into in Figure 0-57. For refrigerator every extra plus means the efficiency is 20% better compared to the A standard. For every home appliance there are separate differences of energy savings between the classes.
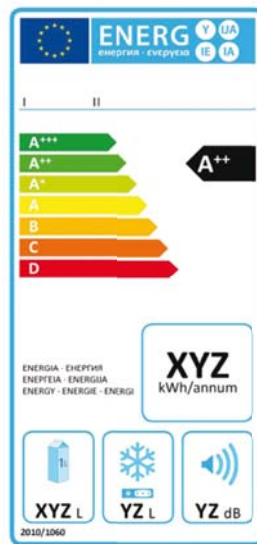
Figure 0-56:   *EU-Label Refrigerator*
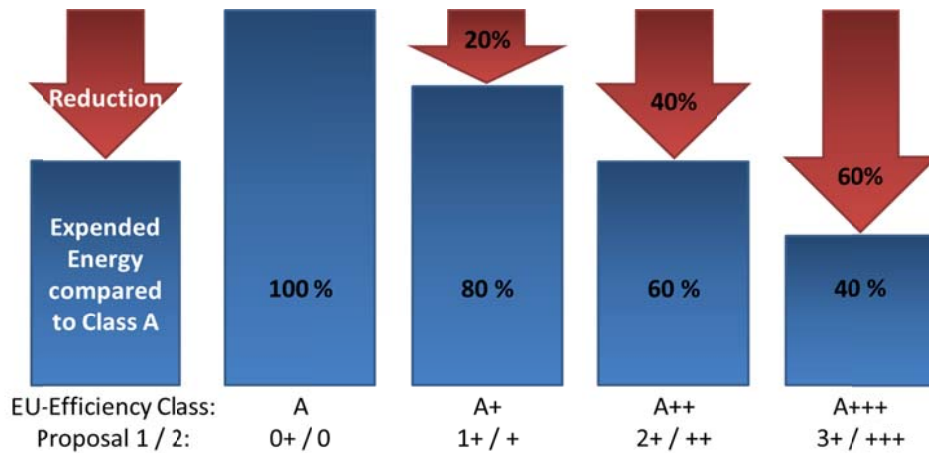
Figure 0-57: *Energy Saving Comparison Class A to A+++ for Refrigerators and a Proposal for the Efficiency Labels*

Optimizing for a "Smart" Grid

The main focus has to be optimizing grid design at a view of following aspects:

- Optimizing …
- Boosting …
- Extension …

… of grid transport lines

- Improve Efficiency
- Use of Weather prediction
- Minimizing energy transportation needs (decentralisation)

Efficiency Improvements

Efficiency improvements can change a lot. We have to decide to save energy we really need or what is used for comfort. The simplest energy efficiency increase can be done by the consumer. For that reason an energy information system and training with a consultant how to cut down energy consumption should be mandatory for every residential home.

For example I installed a three phased meter at my flat. The energy meter of OWL (see Figure 0-58) measures currents. The metering receiver is data storage and monitor in one box. The measuring device is powered by battery and transmits an average value of the current every six seconds. The standard voltage is set to 230 Volts. The metering receiver can be connected via USB to a computer. The meter

can show the momentarily current or multiplied by the voltage power. Also via a factor the carbon dioxide emissions can be viewed. The meter makes it possible to measure instantly the load and check for idle consumers. One big idle consumer was found so far in my flat. After two month of measuring the stove and oven were identified to consume 110 W in idle mode. At an Energy price of 24 €cents/kWh and 8000 h of idle time a year this accumulates to 192 € savings a year. The inconvenient part is that the fuse of the oven/stove is incapable of remote control. Fuse and kitchen are separated by 13 meter of foot walk.

Figure 0-58: *OWL metering receiver and data storage* **Figure 0-59**: *OWL metering system: All-in-One: Metering and radio transmitter*
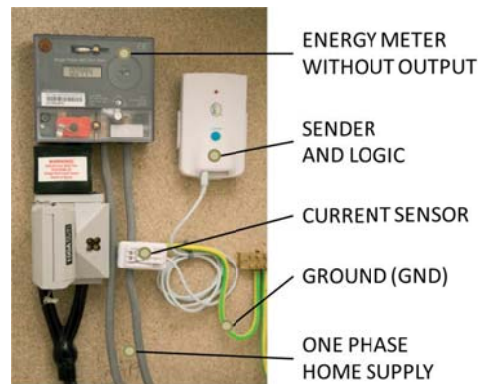
Training energy saving techniques and methods should be offered with every high power, enduring idle or luxury product. At home energy efficiency can be easily improved by replacing inefficient consumers from these main groups:

- Energy saving equipment e.g. stove, oven, toaster, fridge, freezer, power supply unit for computers, washing machine and dryer

- Lightning
  e.g. LED-bulbs, Fluorescent lamp

Weather Prediction

Using weather prediction, energy production of renewable energy sources can be forecasted. In terms of excess energy which cannot be handled by the grid, the battery could shave peaks of the generation. If a beautiful sunny day is forecasted the battery shall discharge to a low SoC level during the night before. Also the battery can be supply power to the grid in the night if possible. The feed into grid power than can be optimised only to charge the battery in case the generation exceeds the guidelines of the ESC. For example in case the PV system is featured with the 70 % cut off this energy can be stored. The PV peaks can be shaved off. In case the energy input is not predicted to charge the battery entirely till dawn the algorithm is

supposed to change. A reduction of feed into grid energy to zero is the conse-
quence. Weather prediction helps ESCs to optimize the load profiles and therefore
the usage of power plants, storages and in future controllable active loads (see next
chapter).

Controllable Active Loads

Instead of electric energy storages for stabilising the grid of the future also loads
have to be applied. The loads should be remotely controlled to start and stop. A load
of that kind is called Controllable active loads (CAL) which are noticeably investigat-
ed (34). CAL systems are no devices that can supply power back into the grid. They
can only make use out of energy prediction and excess energy. For example a stor-
age heater can be charged to its maximum level in time with high grid generation
and keep the warmth during days with low excess energy. Directly used electric en-
ergy is better than a conversion into an electric storage solution and then powering
again the power grid or local loads. Almost every household is connected over the
internet. A miniature server with ARM processing units can be connected to the
power LAN standard. The power LAN enables an easy communication platform.
New electronic devices can be connected to the network just by plugging the plug in
the power outlet. In the following four chapters electronic devices are categorized
which can be addable to a "smart" system of a residential home. The CAL-function
of the load can be switched off. The stop function stays on, if the grid is destabilized.
Also in case certain demands of loads are gathered an entire plant can ramp up to
supply the consumers. But this case might not be applied very often. In the following
Table 0-43 manageable loads are shown and what energy can be switched off or
on.

Table 0-43:   *Controllable Active Loads (CAL)*

CAL consumer	Power Range from … to … in W
Fridge	100 … 200
Storage heating or cooling	1000 … 3000
EV	1000 … 22000
Washing machine	1000 … 3000
Dryer	1000 … 3000
Dish washer	1000 … 3000

The server gets a location number so the energy supply company (ESC) knows
where the load is connected. The orders are than summarized at the next trans-
former station where the current load is registered and hand it over to the main
server as a packed data file. The operator server allows certain categories to start or
in case the grid is destabilized to shut off. Also a CAL electrical outlet can be in-

stalled. If the grid is destabilized the "STOP" command is transferred to the outlet until stability is proven by a quick ramping up plant (e.g. gas and steam (GaS) power plant). This outlet is the only one which offers full power output with a 16 A fuse. A 16 ampere fuse allows a power output of 3680 V (16 A * 230 V). All other connection should be set to only use 575 W (2.5 A fuse). These two outlets should be marked in different colours, e.g. white or black for the low 2.5 A fuse and with green/red LED light the high power outlet: Green at stable grid and red when unstable. If the light shows red the outlet is disconnected from the grid. This inconvenience is compensated by the stability of the grid.

Load Shifting Analysis

Load shifting analysis is similar to CAL. The difference is the intelligent shifting of loads is done within a single system to optimise. The loads are not controlled by the ESC but rather from the owner system. Loads can be shifted from times during heavy loads to off peak times. Many appliances at home neither care when they are run nor do the people who are you using them. A control system can be easily applied and would be a mass product. Easiest connection procedure is the internet. The consumer can log onto a server and should tell the energy supply company:

1. When do I want to start at least, so I am finishing right in time?
2. How much energy do I need? Inclusive 5 min profile number.
3. Where am I located in the power grid?
4. How important am I?

This data can be stored on a server and be compressed for the next server. The most convenient factor is that unimportant loads can be cut of the grid. First main application might be electronic vehicles (EV). The charging control should implement the communication device. Smart loads should also be connected to the grid nearby where the energy is engendered. These consumers are theoretically able to do load shifting:

Application => Power || v	Thermal	Electric
< 100 W	**Fridge** Cool down to low temperature	Charge batteries: • eBike 25 km/h • Cloud computer
> 100 W	**Heat elements :** • Drinking water • Dish washer • Washing machine	Charge batteries: • Vacuum cleaner • Vehicle • eBike 45 km/h

AKD-Batt Design Tool

Abstract

This project is focusing on "Renewable Energy Balancing for residential Homes". Cost for electric energy is continuously rising. Therefore a positive trend towards self-consumption of decentralized-produced energy can be observed. Renewable sources like photovoltaic or wind are occurring in rather fluctuating manners. To increase the self-consumption storage solutions are needed. Batteries meet the specifications a storage system needs for a residential home. Batteries are small and powerful.

The scope of this project is to find out:

"How much battery capacity is needed for a residential home and how much self-consumption can be achieved with it?"

A MS-Excel-based program-tool has been developed to guide the design process. The main requirement for this tool was to be easy-to-use. A particularity is the user-definable load and generation profiles. Self-consumption can be increased to encouraging high levels, whenever the renewable energy generation is both frequent and sufficient.

Kurzfassung

Dieses Projekt fokussiert sich auf das „Regeneratives Energien-Management für Wohnhäuser". Kosten für elektrische Energie steigen stetig. Aus diesem Grund gibt es einen positiven Trend zum Eigenverbrauch dezentral erzeugter Energie. Das Auftreten von regenerativer Energie aus Photovoltaik und Wind sind von starken Fluktuationen unterlaufen. Von Nöten ist eine Speicher Lösung, um den Eigenverbrauch zu steigern. Batterien erfüllen als Speicher die Anforderungen von einem Wohnhaus, da diese klein und leistungsstark sind.

Im Rahmen des Projektes ist zu ermitteln:
„Welche Dimensionierung der Batteriekapazität ist nötig für ein Wohnhaus und wie viel Eigenverbrauch kann damit erreicht werden?"

Ein Programm wurde entwickelt zur Überprüfung der Auslegung. Die Anforderungen wurden auf eine einfache und leicht handhabbare Software gelegt. Die Berechnung erfolgt als Besonderheit über eigens anpassbare Last- und Generator-Profile. Eigenverbrauch kann zu einem zufriedenstellenden Maße erhöht werden. Die Bedingung dafür sind fortlaufende und hinreichende Energieerträge von der Generator Seite.

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List of Abbreviations

DoD	Depth of Discharge
ESC	Energy Supply Company
ICQ	Internal Consumption Quote
SSQ	Self-sustainability Quote
kWp	kilo Watt peak
PV	Photovoltaic
SoC	State of Charge
VBA	Visual Basic for Application (language)

Introduction

Welcome to the

PV Battery Tool

Here is a short overview of how a battery system works:

(1) PV Generator

(2) Inverter

(3) Feed In Meter

(4) Two Way Meter

(5) Battery
- Storage of Excess Energy, if demand is already taken care off
- Power Demand, if Generation is sufficient

(6) Grid
Full Battery:
- Feed In Grid
Empty Battery:
- Power Demand via Grid

(7) Consumer

Quelle: gepowercontrolscom

Basics for Software Development

Methodology

The methodology contains the step by step proceedings of the program design and operation procedures. The PV battery program was designed to be with KISS approach (Keep it short and simple). Therefore Excel and the integrated Visual Basic for Applications language (VBA) were chosen as program platform. The office product is wide spread.

First approach:

- One generator profile

- One H0 load profile

- One ideal storage "bucket"

One generator (photovoltaic) supplies the consumers of a residential house in addition to the grid. The consumption of the house hold is described via a standardised load profile called H0. H0 is the only profile for residential homes. For non-residential homes there are other profiles like G0 for business, N0 for night powered heaters, L0 for farmers and A0 for Traffic lights.

The profile H0 is an average of 150 households. Time steps accuracy is 15 minutes. The interval size of 15 minutes is used as default by utilities for accounting. The PV data was obtained via SQL database of GE Global Research Europe in Garching near Munich. The one second accuracy was summed up to 15 minute means.

The load and generation profiles can be subtracted for reckoning the energy value which has to be charged or discharged (see Equation 0-1):

$$\text{Battery Energy Discharge} = \text{Load Energy General} \; - \; \text{PV Generation}$$

Equation 0-1:   *Equation for Battery Energy Discharge*

The battery calculation algorithm was designed next. Excess energy is stored to the battery within set boundaries. Energy is supplied by the battery as long the minimum state of charge is not reached. The internal consumption quote in the program is applies to the total load data and not to the total generation.

The first extension stepped into action soon afterwards. Three more generators and loads can be added to the calculation. Efficiency for the battery was added. Losses for charging and discharging can be set to different efficiency values.

To exchange the profiles more comfortably, instead of copy paste procedure, a macro (VBA-function) enables the user to easily do the exchange.

Definitions

Definitions make understanding much simpler. For example battery is often used as a synonym for a rechargeable battery. In the sub-chapters following items will be declared:

- Generators and Loads
- Internal Consumption and Self-Sustain Quote
- Battery States

Generators

Generators produce electric energy. The energy values are set in profiles. Four generators are applied as shown in Table 0-1. The generation profiles have to be in 15 minute intervals for a whole year.

Table 0-1:   *Generators for PV-Battery-Tool*

Generators
Photovoltaic (PV)
Wind
Combined Heat and Power (CHP)
GenX*

* GenX is open for a back-up generator or a self-defined generator

Loads

Loads consume electric energy. Loads are a gathering of residential appliances or high power consumers like the heat pump or an electric vehicle. The energy values are set in profiles. Four loads are applied as shown in Table 0-2. The load profiles have to be in 15 minute intervals for a whole year.

Table 0-2:   *Loads for PV-Battery-Tool*

Loads
General (entire Household)
Car
Heat Pump
LoadX*

* LoadX is an open profile for a self-definable load

Internal Consumption and Self-Sustainability Quote

The internal consumption quote used in the program is the self-sustainability quote de-scribed as SSQ. Since the system is not meant for 100% self-sustainable residential homes it is still marked as internal consumption.

Internal Consumption Quote (ICQ)

The EEG law defines the internal consumption quote as the energy used from PV by en-ergy produced from PV. The energy used from PV is the energy produced from PV sub-tracted by the energy fed into grid. The internal consumption quote can be seen in fol-lowing Equation 0-2:

$$ICQ = \frac{Energy\ produced\ from\ PV - Energy\ fed\ into\ Grid}{Energy\ produced\ from\ PV}$$

Equation 0-2:   *Internal Consumption Equation by EEG*

Self-Sustainability Quote (SSQ)

The EEG internal consumption equation does not describe the real ratio of the total used energy at home to the used energy from Generators. The following Equation 0-3 de-scribes the self-sustainability grade of system.

$$SSQ = \frac{Energy\ produced\ from\ Generators - Energy\ fed\ into\ Grid}{Used\ Energy\ at\ Home}$$

Equation 0-3:   *Equation of Self-sustainability Grade based on Used Energy at Home*

ICQ describes the degree of utilisation of the generator while the SSQ describes the utili-sation condition of the entire.

Examples for the ICQ and SSQ equations:

Only a small PV system with 2 kW is considered. Over a year it produced 2000 kWh. An Energy amount of 1000 kWh was supplied to the grid (fed into grid). 4000 kWh have been supplied by the grid by the energy supply company (ESC) / utility.

For Equation 0-2:

$$ICQ_{example} = \frac{2000\ kWh - 1000\ kWh}{2000\ kWh} = 50\ \%$$

For Equation 0-3 used Energy is supplied energy from ESC + (Energy produced from PV – Energy fed into Grid):

$$SSQ_{example} = \frac{2000\ kWh - 1000\ kWh}{4000\ kWh + (2000\ kWh - 1000\ kWh)} = 20\ \%$$

Equation 0-3 is the equation used in the program.

In the following charts are the characteristics of IC and SSQ shown. The chart is standardised for 10.000 kWh/a of general load, the battery capacity is zero. Figure 0-1 and Figure 0-2 shows the IC and SSQ in dependency of the PV Generator size. In the first chart PV generator size is step by step increased linearly to 20 kW power and in the second chart scaled logarithmically. Standard utilisation is one thousand hours per one kW installed power.
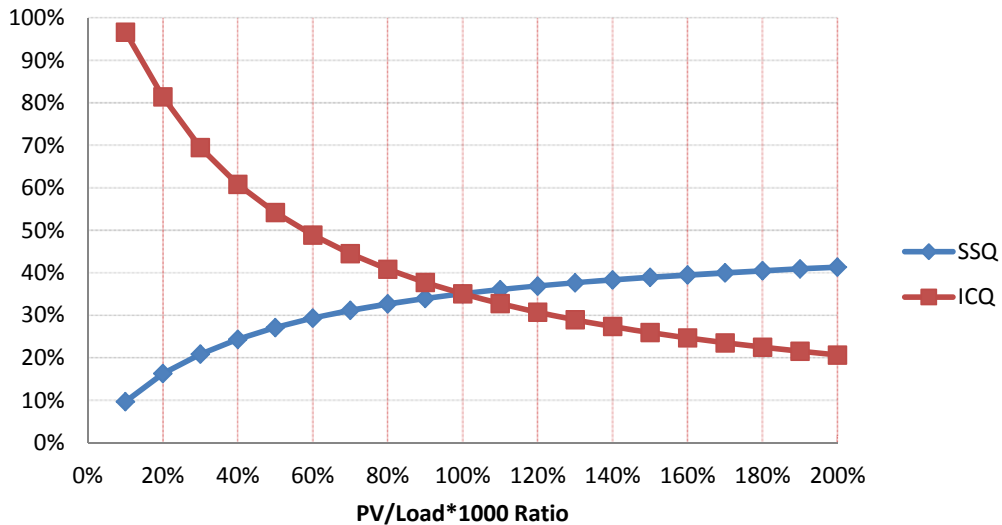

Figure 0-1: *ICQ and SSQ scaled linear to PV size multiplied by a utilization time of 1000 h divided by Load*
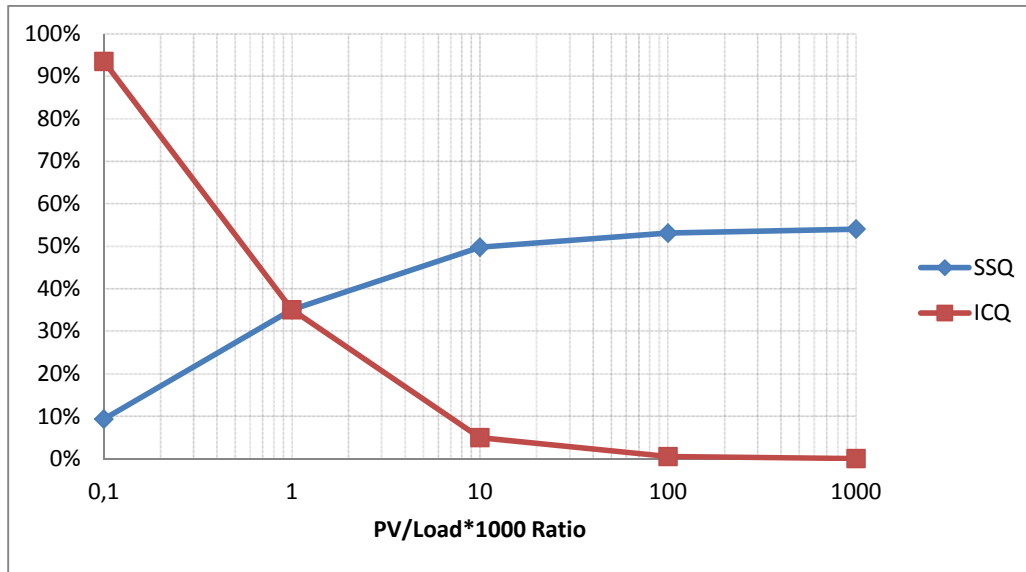
E

Figure 0-2:   *ICQ and SSQ logarithmically scaled*

Looking at the equations for ICQ and SSQ there are three ways to improve the internal consumption quote respectively the self-sustainability grade:

1. Increase power output from generators / PV

2. Decrease energy feed into grid

3. Decrease energy use at home

These three steps refer to many possible options:

at 1.   Install a more powerful PV generator,
         a small additional generator to provide at every time of day.

at 2.   Usage of a storage,
         adjust energy consumption behaviour,
         switch loads to sun shine hours (decrease idle load)

at 3.   Buy class A to A+++* labelled equipment, pay attention to idle loads

        *EU Classes A to D see Annex page A

In this project each point is considered, but the focus will be on storage dimensioning.

Battery Load States

Battery load states define the stored energy level. There are many boundaries to describe the battery state.

SOC max and min of the battery

If the battery is fully charged the maximum state of charge (SoC) is reached and the battery is labelled full; SoC_{max} is therefore reached. If the battery is totally discharged this state is called empty also SoC_{min} with a state of available charge of zero. For maximum and minimum SoC see Figure 0-3.

SOC max of the battery and allowed minimum

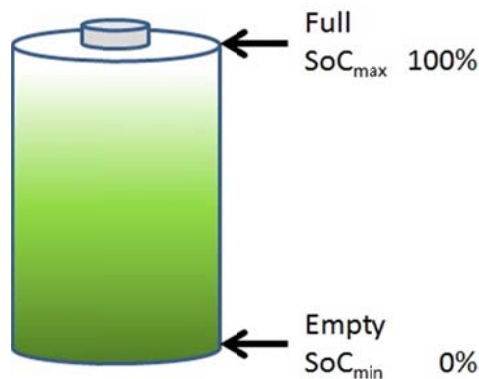Batteries are normally not allowed to discharge beyond a certain allowed minimum SoC_{min} (see Figure 0-4).

Figure 0-3:   *SoC Maximum and Mini-*   **Figure 0-4:**   *SoC Maximum of Battery and*
                mum of Battery   *Allowed stated Minimum*
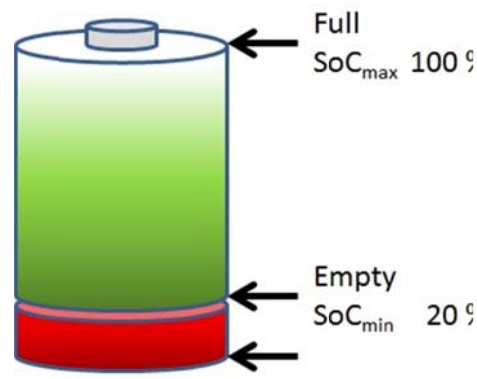
SOC allowed maximum and minimum of the battery

The maximum SoC is normally stated 100%. In many cases also a reduced charging voltage reduces stress and increases the life time of the battery. There are two possibilities shown in Figure 0-5 to define the SoC_{max} with a percentage. The maximum SoC of the battery can be defined as 100% or the allowed maximum, SoC_{max}, can be stated 100%. For the program development the figure on the right side was chosen. DoD is the contrary of SoC. While the SoC has a zero percentage charge the DoD is at its maximum and vice versa.
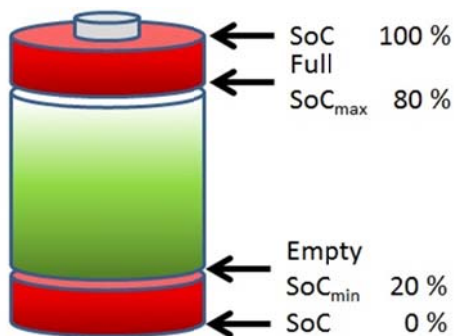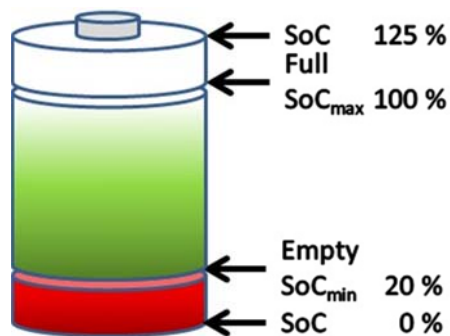

Figure 0-5:   *Allowed SoC Maximum and Minimum are stated*

Cycles per Year

Cycles per year defines the energy input to the battery without further losses divided by the useable capacity of the battery (see Equation 0-4). These cycles are full cycles. The battery is not fully charged each time during the year many. The occurrences appear in case produced energy is insufficient. These cycles are less stressful to the battery.

$$Cyles \ per \ year = \frac{Energy \ Input \ before \ Losses}{Battery \ Capacity}$$

Equation 0-4: *Calculation Cycle Counts per Year*

System Storage Efficiency

Efficiency is the ratio of useable energy to the applied energy. In case of the battery efficiency for charging and discharging are applied (see Equation 0-5 and Equation 0-6).

$$Efficiency \ of \ Storage \ Charging = \frac{Stored \ Energy}{Input \ Energy}$$

Equation 0-5: *Energy Efficiency of Charging the Storage*

$$Efficiency \ of \ Storage \ Discharging = \frac{Output \ Energy}{Stored \ Energy}$$

Equation 0-6: *Energy Efficiency of Discharging the Storage*

Design-Tool for Capacity Dimensioning General

Program features-list:

- 15 Minute Time Steps

- 4 Load and Generators Profiles each

- Easy Exchange of Profiles

- Profile Example view

- Robustness Simulation

- Monte Carlo Simulation

The Simulation Tool is parted in single tabs:

(1) Main Menu

(2) Profile Overview

(3) Parameter Settings

(4) One Year Data Calculation

(5) Monte Carlo Simulation

(6) Robustness Analysis

For each menu a sub-chapter can be found below.

At the bottom of the Excel screen the tab-bar can be found:

The program is structured in six tabs. The following Table 0-3 shows all tabs with a picture.

Table 0-3:   *The six Program Tabs*

(1) Main Menu

(2) Profile Overview

(3) Parameter Settings

(4) One Year Data Calculation

(5) Monte Carlo Simulation

(6) Robustness Analysis

Main Menu

The main menu offers every main entry parameter for generators, loads and battery as well as important output values like energy feed into grid, energy obtained from ESC and battery characteristics (see Figure 0-6). Generation, Load and Battery size are editable. After entering data to the INPUT section - headings marked in light blue - by pressing the Calculate button on the right sight OUTPUT data, the monthly view chart as well as the two days example chart will be updated immediately. For an even more detailed analysis click "Goto Monte Carlo Simulation" next to the "Calculate" button.

The main menu supports the three sections:

- Input
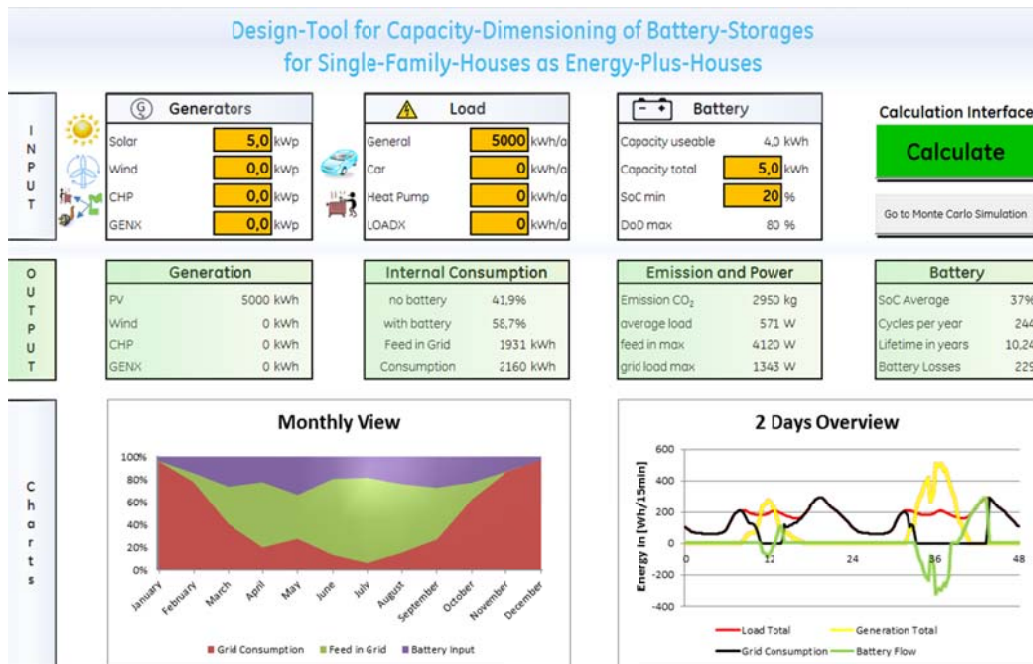
- Output

- Charts

Figure 0-6:   *Main Menu Tab: Input, Output, Charts and Calculation Interface*

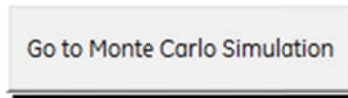## Interface

Calculation Interface

The Calculate button will change colour if an input value is changed.

Red – not yet calculated

Green – calculated

For a more detailed simulation press the Monte Carlo Simulation button. More information you will find in chapter 0.

Easy Exchange Interface

The button "Exchange Profile" will replace any profile easily. Via the drop-down menu the profile to exchange can be chosen. The specific folder will open and a selectable list of profile will be shown.

The profile file consists out of the heading and 35040 rows of data. The profile needs to have 15 minute average values and start with first of January 00:00 and end on December the 31st 23:45. In Table 0-4 an example is shown of how the *.xlsx file (Windows Update adds compatibility for EXCEL 2003 Version) have to look like:

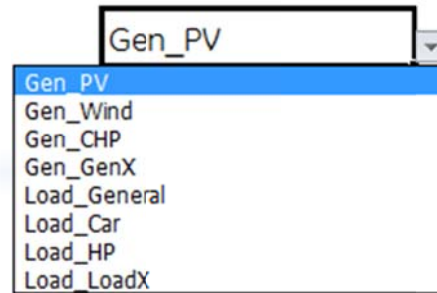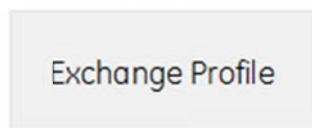*Table 0-4:*   *Example cut-out Profile Table*

Time	Value
01.01. 00:00	123
01.01. 00:15	234
⋮	⋮
31.12. 23:45	345

Input

Generation

Values for Rated Power in kW for generators:

- Solar
- Wind
- Combined Heat and Power (CHP)
- GENX *

* GenX is open for a back-up generator or a self-defined generator.

Generators		
Solar	5,0	kWp
Wind	0,0	kWp
CHP	0,0	kWp
GENX	0,0	kWp

Load

The load box preserves data in energy per year for following consumer:

- General
- Car
- Heat pump
- LOADX *

* LoadX is an open profile for a self-definable load.

Load		
General	5000	kWh/a
Car	0	kWh/a
Heat Pump	0	kWh/a
LOADX	0	kWh/a

Battery

The battery box allows entering following battery parameters:

- Total Capacity
- Minimum allowed State of Charge (SoC$_{min}$)

Useable Capacity will then be calculated.

The battery parameter for the upper bound can be changed in the parameter settings (see chapter 0 "Parameter Settings").

Battery		
Capacity useable	4,0	kWh
Capacity total	5,0	kWh
SoC min	20	%
DoD max	80	%

Output

Generation

Due to the kWp normed profiles the generation profiles are multiplied by the rated Power. PV also takes usage hours into account:

$$Factor = \frac{P \ (radted \ Power) \times t \ (in \ hours)}{1000 \ kWh}$$

Generation	
PV	4706 kWh
Wind	0 kWh
CHP	0 kWh
GENX	0 kWh

An Example:

Pr = 5 kW

t = 942 h (Berlin)

$$Factor = \frac{5 \ kWp \times 942 \ h}{1000 \ kWh} = 4.7 \Rightarrow$$

Energy Generation per year: 4706 kWh

Internal Consumption Quote (ICQ)

This Area shows the ICQ without and with an installed battery system. Also the grid consumption and feed into grid energy is shown.

Attention:
The ICQ used in the program is the SSQ defined in chapter 0.

Internal Consumption	
no battery	41,7%
with battery	58,3%
Feed in Grid	1703 kWh
Consumption	1895 kWh

Emission and Power (EP)

The EP field supports data to saved CO_2 emissions, if all sources are stated renewable. The factor therefore is 590 kg per MWh. In addition the maximum feed in grid and grid load is added.

Emission and Power	
Emission CO_2	2777 kg
average load	542 W
feed in max	3873 W
grid load max	1276 W

Battery

State of charge (SoC) shows the average charge status over the whole year, which can be an identifier for a significantly reduction of battery life time. E.g.: an average over 85 % is bad for storage reasons.

Lifetime in years is based on full cycles.

Battery	
SoC Average	42%
Cycles per year	255
Lifetime in years	9,80
Battery Losses	148

$$Lifetime = \frac{Total \ amout \ of \ achivable \ Cycles \ (see \ battery \ data-sheet)}{Cycles \ per \ year}$$

Charts

In Figure 0-7 a monthly chart shows the energy sum of each month for

- Energy from ESC

- Feed into Grid

- Battery Input

Feed into grid rises till July, green line, while grid consumption is contrary and rises in winter months; the battery throughput depends on the battery capacity. From March to September the battery input is almost identical. The capacity could be increased for higher internal consumption quotes since feed into grid is sufficient and energy has still to be supplied from ESC. Battery input hits its maxima around March and September, due to moderate irradiation and moderate energy demand. In summer the energy input is lower. There is much excess energy and demand is at its minimum. The battery is probably not even discharged during the night. For that reason the grid consumption hits also a minimum. The battery is not efficiently used between the months October with February. At this time, for better battery life expectancy the charge algorithm should be optimized for a higher average state of charge.
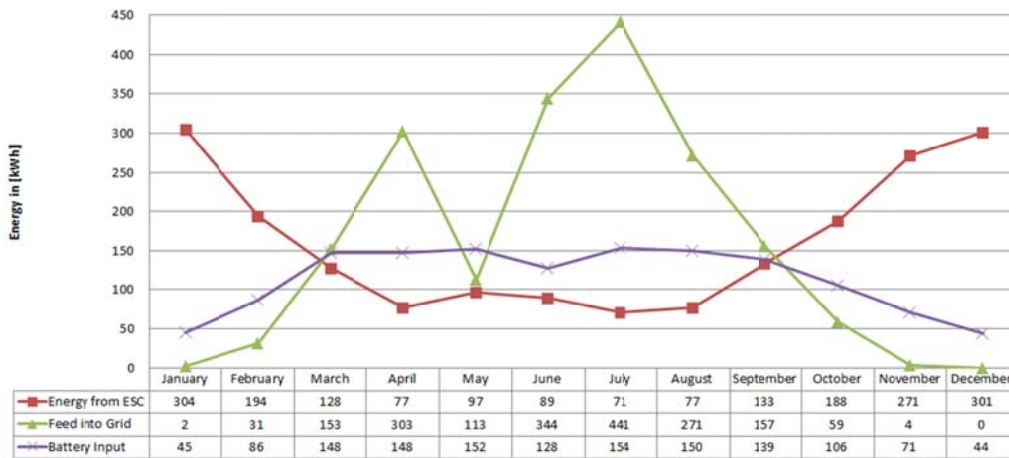

	January	February	March	April	May	June	July	August	September	October	November	December
Energy from ESC	304	194	128	77	97	89	71	77	133	188	271	301
Feed into Grid	2	31	153	303	113	344	441	271	157	59	4	0
Battery Input	45	86	148	148	152	128	154	150	139	106	71	44

Figure 0-7:   *Monthly chart: Energy supply by ESC, feed into grid and battery input*

The following Figure 0-8 shows the ratio between the three energy sums in every month as 100 % in an accumulated view. Example July (data obtained from chart; see Figure 0-7):

$Energy\ Supply\ from\ ESC = 71\ kWh$ $Sum = 71 + 441 + 51 = 563\ kWh$

$Feed\ into\ Grid = 441\ kWh$ $\Rightarrow ESC = \dfrac{71}{563} = 12.6\ \%$

$Battery\ Input = 51\ kWh$ $\Rightarrow Feed\ into\ grid = \dfrac{441}{563} = 78.3\ \%$

$$\Rightarrow Battery\ Input = \dfrac{51}{563} = 9.1\ \%$$
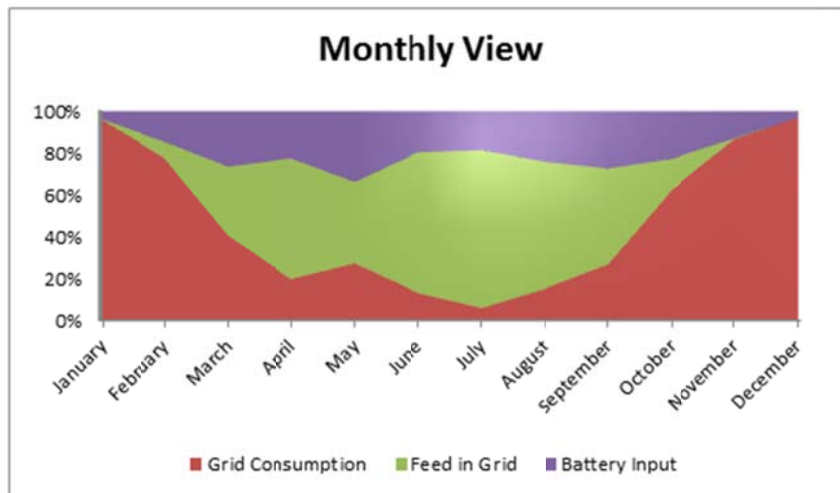
Figure 0-8: *Grid Consumption, Feed in Grid and Battery Input summed up every Month as 100 % and set into ratio*

The two day overview is an example of data in February (see Figure 0-9). The chart shows generation (yellow), battery in and output (green) under the defined efficiencies, grid consumption (black) and the current load (red). All data are directly calculation values and therefore in watt hours per 15 min Intervals. The average power is extracted by multiplying the energy values by factor four Watt per Wh/15min.
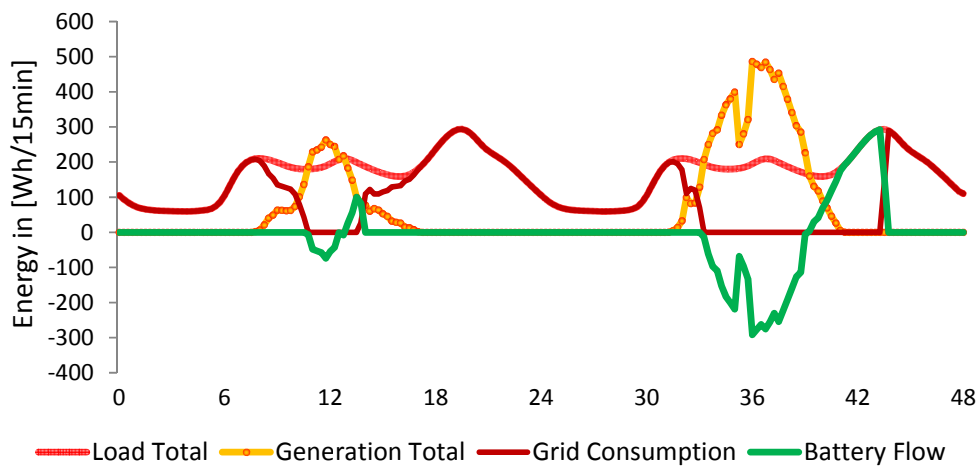
Figure 0-9: *Two days overview of the energy balancing of PV Battery system*

Profile Overview

The profile overview enables the view to the different profiles. The profiles can be shown in detail by disabling the other graphs by clicking the buttons shown in Figure 0-10. The load and generation graph has an all on/off button each to show or hide all

loads / generations and enable the user to quickly display one graph again by activating it.
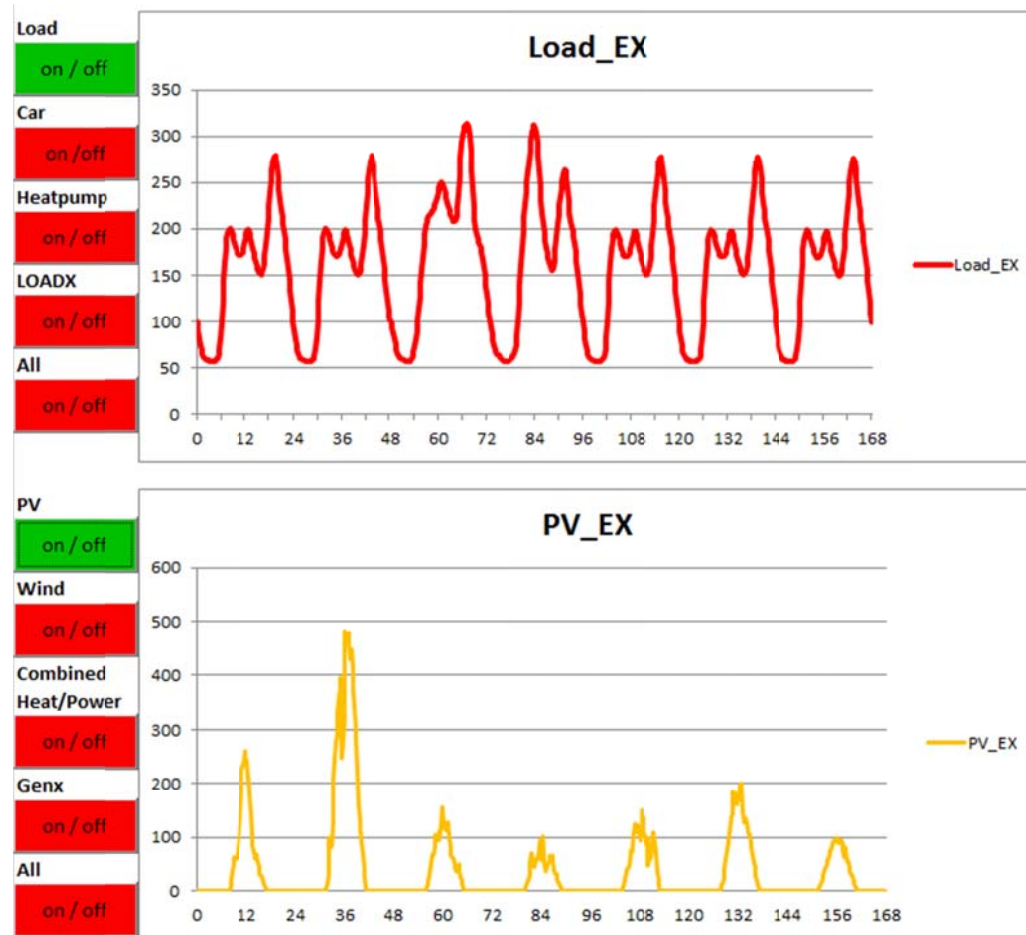

Figure 0-10   *Profile overview example of loads (first chart) and PV generation chart (second chart)*

Parameter Settings

The parameter settings tab give you the total overview of enabled and used parameters (see Figure 0-11). Data from the main menu is marked blue. The advanced settings are marked orange. A list of the editable parameters and reasonable range values can be found in Table 0-5. Generation and battery data can be edited in more detail. The blue marked fields are a copy from the main menu to give an overview of all parameters in one tab. The blue fields will be overwritten if changed in the parameter settings tab. Orange labelled fields can be edited, not filled cells are open for further implementation

Table 0-5:   *Parameter and Reasonable Range Values*

Parameter	Reasonable Range
70% PV cut off	On / Off
PV – Hours	700 ... 2000
PV to Inverter Ratio	0.9 to 2, 3 ...
Batter – Lifetime Cycles	800 ... 7000
Battery – average Input / Output Efficiency	0.8 ... 0.99
Battery – Maximum Charge Level (SoC$_{max}$)	0.8 ... 1.0

Generators		DATA			Cost and Subsidies	
PV	5 kWp	70% cut of control installed?	FALSE	Unit	PV exclusive Tax	2500,00 €/ kWp
		Hours (specific Yield)	942	kWh/kWp	grid in < 30 kWp	0,24 €/kWh
		Berlin 942 München 1050			SC < 30%	0,08 €/kWh
		PV to Inverter Ratio	1		SC > 30%	0,12 €/kWh
		Pmax		1 kW/kWp	Tax	475 €/kWp
Wind	0 kWp				Wind	1500,00 €/kWp
CHP	0 kWp	Start date	10		CHP	2000 €/kWp
		Duration in month	6		CHP electric cost	0,28 €/kWhel
		CHP 1/η	4		KWK	0,055 €/kWh
GENX	0 kWp				GENX	€/kWp
					specific cost	€/kWhel

Load		DATA	Function	Ratio	Cost	
General	5000 kWh	Variation with different funtior DC + sin		1	EVU / ESC	0,24 €/kWh
Heat Pump	0 kWh					
Electric Car	0 kWh					
LOADX	0 kWh					
load_data_load	5000 kWh					

Battery Data					
DODmax	0,80	Lifetime Cycles	2500		
Capacity in Wh	4000 Wh	Effiency charge	0,85	Eff_total	
Pmax	4000 Wh/15mi	Effiency discharge	0,9	0,765	
Capacity Total Wh	5000 Wh	factor Wh/(Whbat*15min)	1		
		Maximum Charge	0,85		

Special Data		
Tax	19 Germany	

Figure 0-11:   *Parameter Settings Tab: Blue fields, copy of main menu. Orange labelled fields are additional parameters*

One Year Data Calculation

The one year data calculation tab contains all necessary calculations and data for a one year simulation. The display shows sums of all energy values and the multiplication factors. The first column supplies the time information in the format DD.MM.YYYY and time hh:mm. D stands for day, M for Month, Y for Year, h for hour and m for minute. The calculation columns are marked with orange front colour on grey back colour. The Indexes in the one year data calculation tab are found in Table 0-6.

Table 0-6:   *Indexes used in the in One Year Data Calculation*

Index	Explanation
E	Energy
0	Standard Profile
X	Standard Profile Multiplied by factor X
Inc	Inclusive
-	Consumed from
+/-	Feed in / consumed from

Load data for the four different loads are contained in columns B to I. Column B contains the standardised profile LoadE0, while column C contains the multiplication with the Load-multiplication factor. Generation data for the four generators are contained in columns J to Q. The sum of all loads per 15 min interval is found in column R. The sum of all generation per 15 min interval is found in column S. The value for load subtracted by generation is the basis for the battery charging calculation (column T). Column U contains the state of charge energy of the usable capacity in [Wh]. Columns V to X contain battery characteristics. Columns Z to AB contains the energy supplied via the distribution grid and energy feed into grid. Column AC contains the SoC value of the total battery capacity. The simulation requires 15 minute interval averages on Energy in Wh, resulting in a 35040 rows of data for one year. Load Profiles have to be normed to 1000 kWh per year. Generation Profiles are normed to their full time usage hours or to general 1000 kWh per year. In Figure 0-12 a basic overview of the one year data calculation is shown. The basic view features a minimisation of loads and generation to the general residential load (Load_EX) and a photovoltaic system (PV_EX). The battery columns were reduced to the important columns without any battery losses.

Figure 0-12 One Year Data Calculation Sheet containing basic view of Loads, Generators, SoC of the Battery and Grid data

Monte Carlo Simulation

The Monte Carlo Simulation (MCS) gives the opportunity to see what bandwidth variety the conclusion can have. The MCS calculate the data by diversifying the loads, generations and battery-sizes. Therefore the loads and generations are changed from plus minus X % with a Gauss-distribution in eleven quantified steps. The battery values are distributed as a Weibull-distribution, due to the fact that batteries mostly do not hit their rated capacity. Also they are affected over time by their usage, which will lead to capacity loss. As conclusion a bandwidth variety with their possibilities of occurrence are given. The parameter can be set.
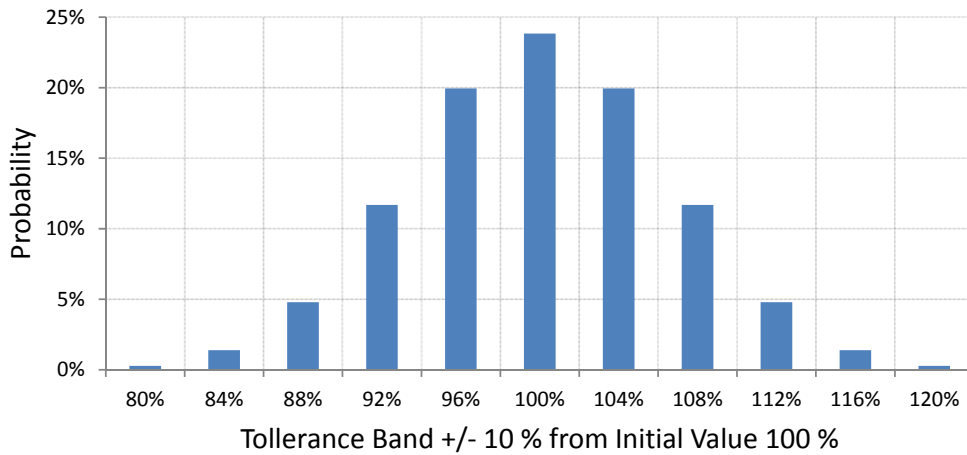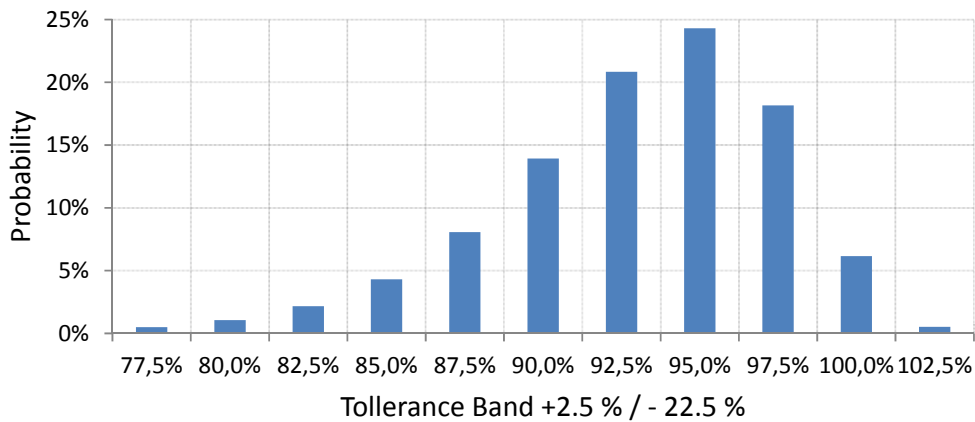

Figure 0-13:   *Gauss-Distribution*

Figure 0-14:   *Weibull-Distribution*

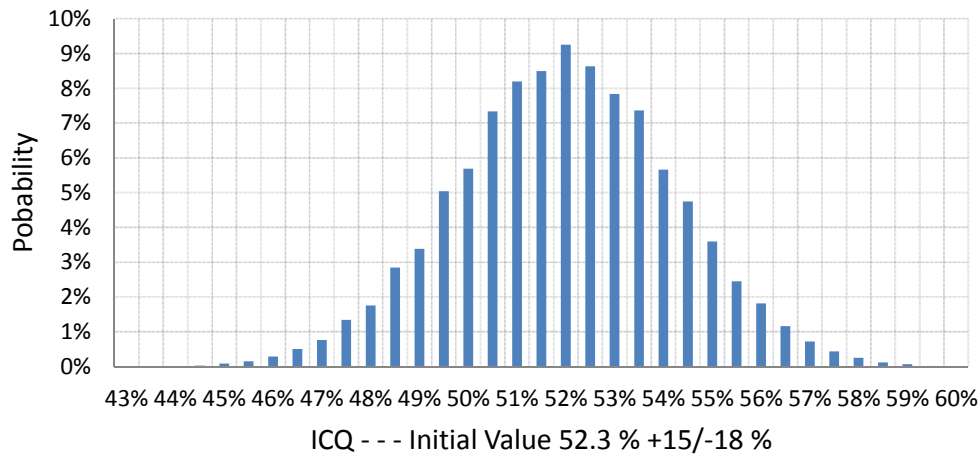Plot for Standard Values: PV 5 kW, Load General 5000 kWh/h, Battery 5 kWh, SoC 20%, Maximum Load

T

Figure 0-15: *Bandwidth – Probability over Internal Consumption Quote*

Robustness Simulation

The robustness simulation is like the MCS an analysis type where more information can be gathered. For robustness simulation ratios are taken into account. There are two ratios: PV to Load and Battery to Load ratio (see Table 0-7). Every output parameter can be displayed as dependency of the ratios which maxes similar sized systems comparable.

Table 0-7: *Ratios for Robustness Simulation*

Ratio #	Ratio between ... and ...	Ratio Calculation
1 PV	Generation PV and Load	$0.1 \dots 2 \ \frac{kW}{1000 \ kWh}$
2 Bat	Battery and Load	$0.1 \dots 20 \ \frac{kWh}{1000 \ kWh}$

Example:

Generation PV and Load Ratio = 1 (Ratio #1 PV)

$Load := 5000 \ kWh$

$$\Rightarrow PV \quad = Load \times (Ratio \ \#1 \ PV) = 5000 \ kWh \times 1 \ \frac{kW}{1000 \ kWh} =$$
$$= 5 \ kW$$

Battery and Load = 2 (Ratio #2 Bat)

U

$$\Rightarrow Battery = Load \times (Ratio \ \#1 \ Bat) = 5000 \ k\cancel{Wh} \times 2 \ \frac{kWh}{1000 \ k\cancel{Wh}} = \frac{2 \times 5\cancel{000} \ kWh}{1\cancel{000}} =$$

$$= 10 \ kWh$$

Similar Systems:

If ratios and additional background parameters (see 0) stay the same technical output values stay the same; economical costs vary.

The results of the robustness simulation are shown in chapter 0.

Calculation for PV-Battery Tool

Calculation General

Calculation for PV-Battery-Tool elucidated the features implemented of Excel and the visual basic for application language (VBA). The calculation in Excel is done via formula written to cells (see Figure 0-16). Another way to execute function is by Macros. Macros can perform more complex functions. Macros can call automatically achieve tasks also doable by hand, but are much faster by using Macros (see Figure 0-17).

	A
1	71
2	441
3	51
4	=SUM(A1:A3)

Figure 0-16:   *Formula in Cell A4 calculates the sum of A1 + A2 + A3 = 71 + 441 + 51 = 563*

```
Option Explicit

Sub BasicExampleAdd()

    Dim Sum As Integer
    Sum = Range("A1").Value _
                        + Cells(2, 1).Value _
                        + Cells(3, 1).Value
    Range("A4").Value = Sum

End Sub
```

Figure 0-17:   *Mini Excel Macro: Sum up 3 values (A1, Cell 2,1 and Cell 3,1) and write them to cell A4. Cell 2,1 is A2 and Cell 3,1 is A3*

Profiles normed (Loads)

The Load profiles are normed to 1000 kWh per year.

The Energy demand x for one time step is calculated by the x kWh/a entered in the Load profile window. Factor R stands for Recalculate or Resize.

$$\bar{E}_{demand\ x} = \underbrace{\frac{x\ in\ [kWh/a]}{1000\ kWh/a}}_{Factor\ R} \times \bar{E}_{demand\ 0}$$

Equation 0-7:   *Calculation of Energy Consumption*

The general load profile is an average of 150 Single-Households normed to 1000 kWh/a.

Resize Calculation Example:

Time   January 1st 00:00

General Energy Demand x   5000 kWh/a

Profile Energy Value   27 Wh (in this 15 min time step)

                                    Power:

$$P = 27\ Wh\ \times \frac{60\ \frac{min}{h}}{15\ min} = 27\ Wh \times \frac{4}{h} = 108\ W$$

⇨   Factor

⇨ $\bar{E}_{demand\ x}$

$$R = \frac{x\ in\ [kWh/a]}{1000\ kWh/a} = \frac{5000\ kWh/a}{1000\ kWh/a} = 5$$

$$\bar{E}_{demand\ x} = R \times 27\ Wh = 5 \times 27\ Wh = 135\ Wh$$

Profiles normed to 1 kW (Generators)

Generation profiles are normed to 1 kW of generator power; except PV; PV is normed to 1000 kWh/a. The PV full time usage hours for the year can be edited in the parameter settings tab. As well the PV to Inverter Ratio can be edited to limit PV generation output.

Battery Algorithm

The battery algorithm is shown by the three sequence charts. The battery system recalls generation and load data (see Figure 0-18). In case generation exceeds the consumption energy the battery switch to the battery charging algorithm, else the battery is discharged. In case load energy is equal to the generation energy the charge algorithm is applied.
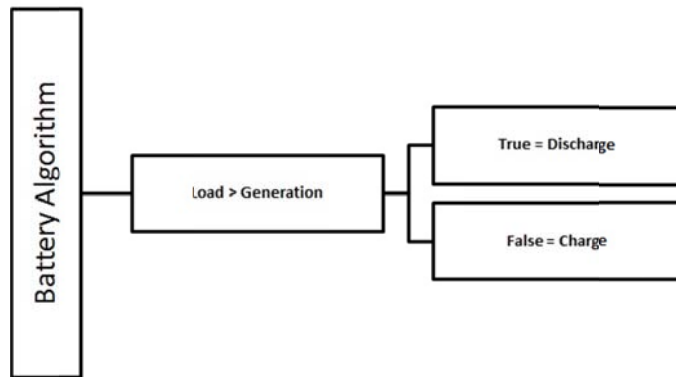
Figure 0-18:   *Battery Algorithm to switch to Charge or Discharge Algorithm*

Battery Charging Algorithm

In case the battery enters the charging algorithm the next step is to recall the actual SoC. If SoC is bigger or equal to the maximum SoC the program checks if the maximum SoC would be exceeded. If so the battery is not charged to the maximum SoC limit. The surplus is fed into the grid. If the last SoC is the maximum SoC all energy is fed into the grid (see Figure 0-19).
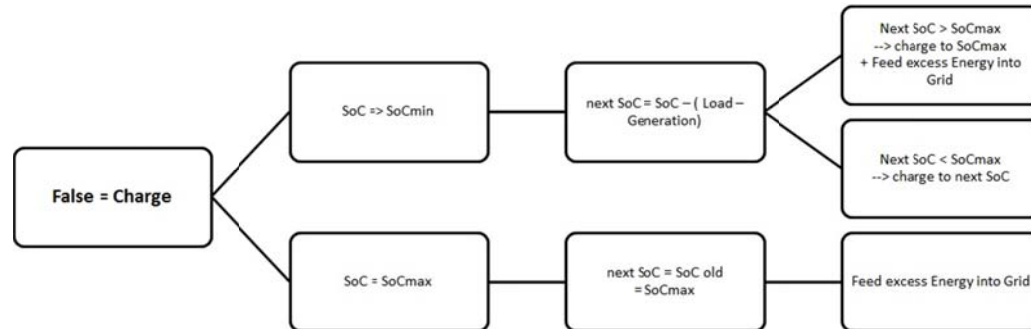

Figure 0-19:   *Battery Charging Algorithm; the steps are checked from right to left*

Battery Discharging Algorithm

The battery discharging algorithm recalls the SoC first. The next step in case of the SoC is lower or equal full capacity but not minimum SoC the battery is discharged. If the minimum SoC would be underrun, the battery is only discharged to the minimum SoC. The remaining demand for powering the loads is withdrawn from the power grid. If the SoC is already the minimum SoC the entire demand is powered by the grid (see Figure 0-20).
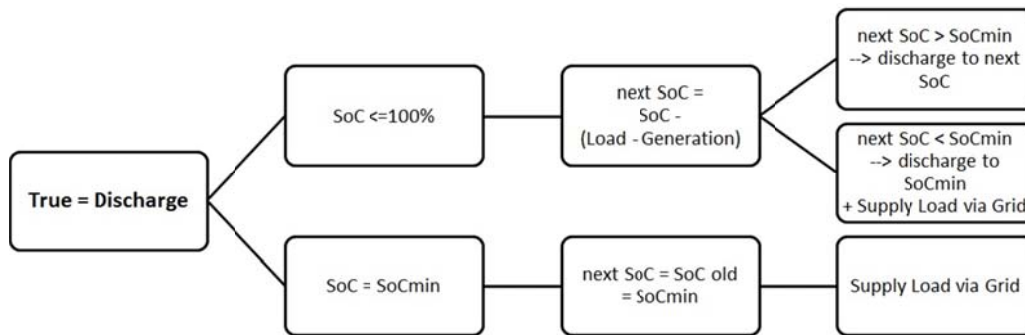
Figure 0-20:   *Battery Discharging Algorithm; the steps are checked from right to left*

PV Inverter Ratio and 70 % Cut Off

The PV inverter ratio and the 70 % cut off are directly implemented to the PV profile (e.g. see Figure 0-21). The 70 % cut off is equivalent of an inverter ratio of one divided by 0.7 resulting in a factor of 1.43. Modern PV plants will have a ratio of 1.4 or higher depending on PV module price and utilisation of the exceeding energy.
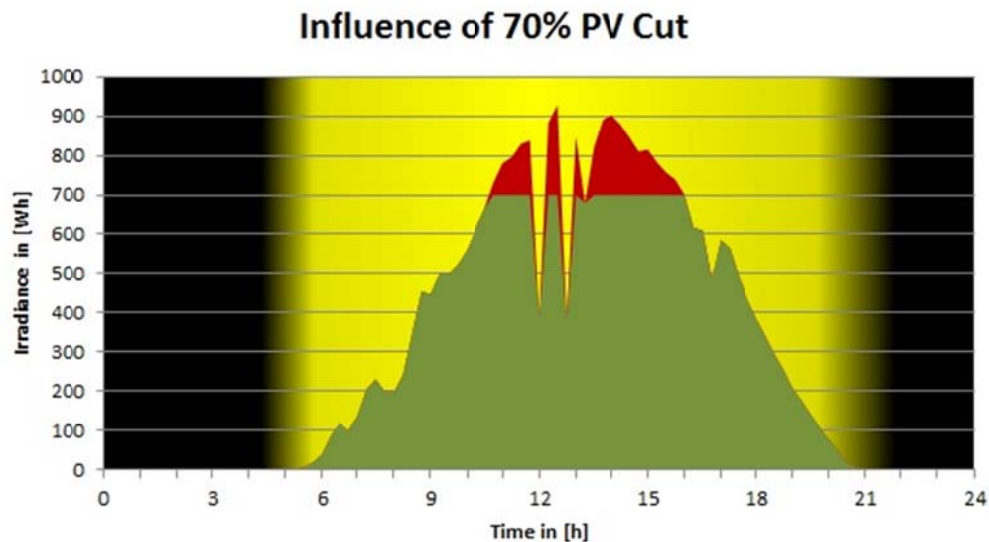

Figure 0-21:   *70 % impacts on energy output of PV generator*

Software Development Method

Program Analysis and Finding Best Parameters

Several simulations were run with different load distributions. For running the simulation the standard generator is PV. Several standard households were defined. For a better compatibility only the ratios of the robustness simulation were taken into account (see chapter 0). The ratios enable the comparison to similar sized systems.

Robustness Simulation

The following diagrams make clear how the internal consumption can be increased. The ratio PV/Load and Battery/Load have to be increased. PV or battery capacity has to be raised or load has to be decreased. The internal consumption and battery lifetime is dependent on the generation and load profiles.

Standard Household 1 features mostly daily concentrated loads during the day and at night no big idle consumers are connected to the system.

Standard Household 2 instead has got electric vehicles, which consumes as much power is the general household load.

Standard Household 3 got a heat pump and electric vehicles which could be enabled during daytime, but the tariff from the energy supply company allows a special contract to just use the heat pump during night hours.

Each standard household is the used data and profile given. The heat pump of "Standard Household 3" the heat pump operation algorithm can be improved by using the heat pump on days with high solar irradiance and other occasions which fit the energy supply company needs. The internal consumption quote rises when generation and load appear simultaneously. The battery is less used and lifetime is increased. If load and generation do not happen simultaneously the battery is able to store the energy and supply it when the generator cannot supply energy. Thus battery is used often and its lifetime decreases. This case applies for PV. The generator only produces power during daytime. Loads which are demanded during night hours cannot be supplied instantly. For each standard household two graphs are shown as well as the used profiles names. Table 0-8 shows

the Inputs and the assigned profiles or data. The profile for load general is my own profile from the first three month of 2012 put together four times for a whole year.

Table 0-8: *Inputs and Profile Assignment for Standard Household 1, 2 and 3*

Input	Profile / Data
Generator PV	PV_Garching_1000kWh
Load General	Rics_Loadprofile_MiddleOfJanuaryToMiddleOfMarch
Load Heat Pump	HP_night_Optimized_0_to_6
Load Car	Car_night_0_to_6_1000kWh_per_year
PV	70 % cut off: No PV/Inverter Ratio: 1
Battery	SoC_{min}: 0 % SoC_{max}: 100 % Cyclestability: 2500 Input/Output Efficiency: 98 %
Ratios #1 PV	$0.1 \dots 2 \frac{kWp}{1000\ kWh}$
Ratio #2 Bat	$0.1 \dots 4 \frac{kWh}{1000\ kWh}$

Chart Interpretation General

The first table shows the lifetime expectation for the battery (see Figure 0-22). The red area shows insufficient battery lifetime, the blue to dark blue area sufficient lifetime up to 20 years and the white area the lifetime between shows the area of medium lifetime expectation. The second table in the sub-chapters named Household 1 to 3 always shows the internal consumption quote over the two ratios (see Figure 0-23). The green area shows the highest, yellow medium and red low internal consumption rates. For a quick comparison the two charts are simplified using less data and compared in chapter 0.
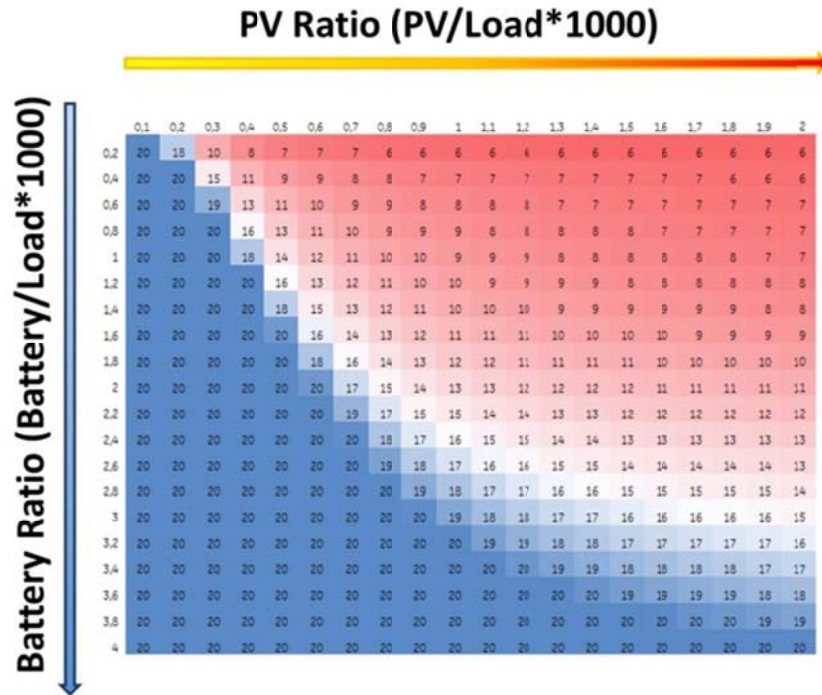
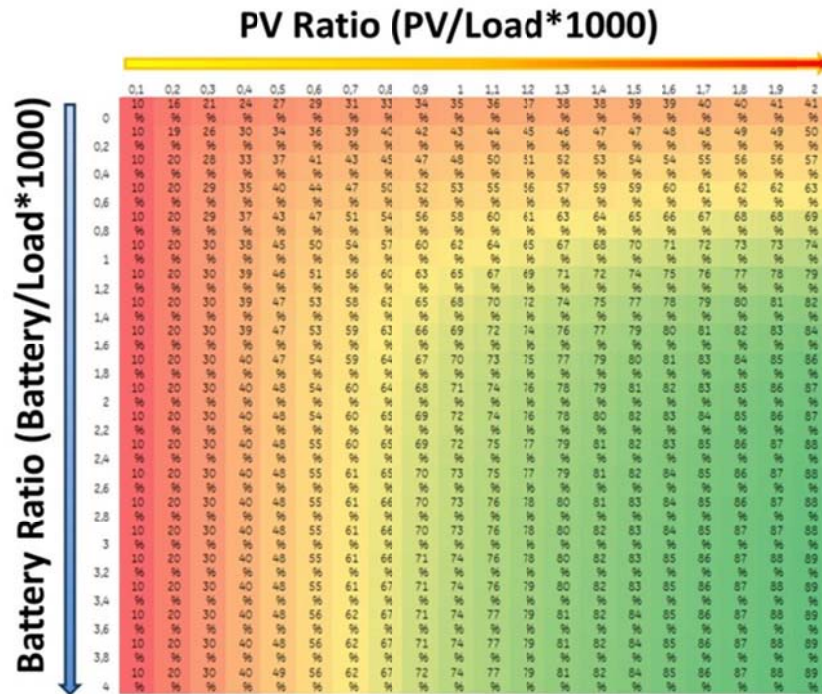*Figure 0-22:*   *Lifetime expectation over Battery Ratio and PV Ratio*

Figure 0-23:   *Internal consumption Quote over Battery Ratio and PV Ratio*

Best Working Conditions

Best working conditions appear when battery lifetime and internal consumption quote gathers an optimum. Following Figure 0-24 shows a compare view of the Household charts. The first rows of internal consumption quote (ICQ) vary widely from 13 % to 41 % of one Household to another. The energy use during night is greatly increased from Household 1 over number 2 to number 3. The total energy consumption is in every case the same but the usage time differs. The internal consumption quote without battery drops dependent on the ratio of energy used during day to energy used during night the ICQ is lower for household 2 and 3 compared to household 1. For the households 1 and 2 ICQ reaches in both terms with big battery (Ratio Battery = 4) and moderate to high PV power capability (Ratio PV = 1 ... 2). The lifetime for household 2 and 3 are decreased significantly. The battery should be large and the PV system should be rated to supply the energy for the whole year to satisfy consumption demand (Ratio PV = 1) to extend lifetime expectancy.
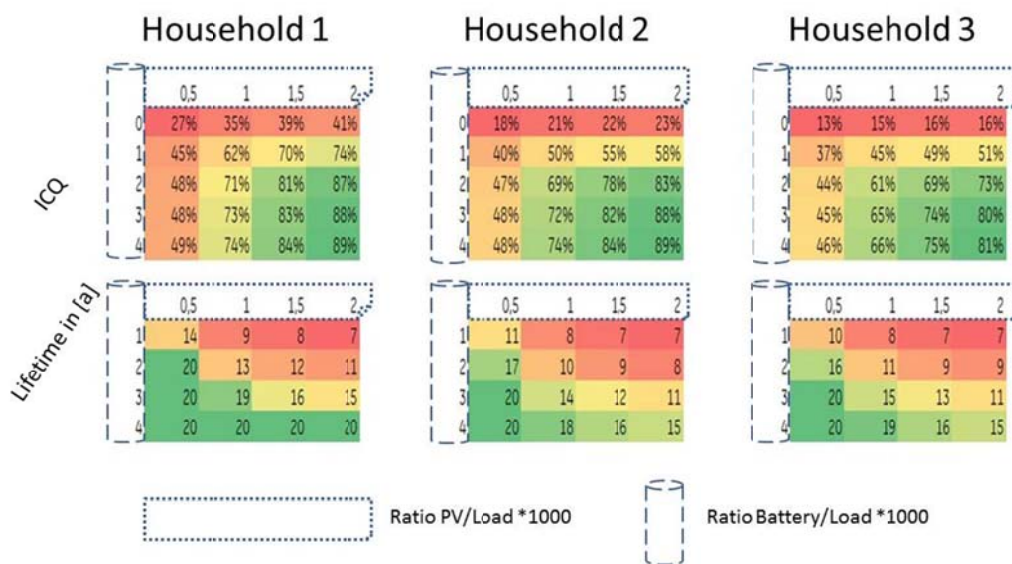

Figure 0-24:   *Overview of all Households*