EVALUATION FOR ELECTRIC ENERGY STORAGE SYSTEM SUPPORTED PHOTO VOLTAIC POWER PLANTS

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"Master of Science"

supervised by
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Affidavit

I, **Dr. Peter Trimmel**, hereby declare

1. that I am the sole author of the present Master Thesis, "EVALUATION FOR ELECTRIC ENERGY STORAGE SYSTEM SUPPORTED PHOTO VOLTAIC POWER PLANTS", 116 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Preface

An U.S. patent application was filed on June 7, 1907, by R. A. Fessenden (granted on November 20, 1917). In it, Fessenden writes:

> *The invention herein described relates to the utilization of intermittent sources of power and more particularly to natural intermittent sources, such as solar radiation and wind power, and has for its object the efficient and practical storage of power so derived.*
>
> *…*
>
> *It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power derived from the intermittent sources of nature.*
>
> *…*
>
> *These sources are, however, intermittent and the problem of storing them in a practicable way, i.e., at a cost which should be less than that of direct generation from coal, has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry, and Brush.*

Abstract

One of the challenges in the area of photovoltaic electricity production is the intermittent production and the required electricity demand. Depending on the actual scenario the use of electrical energy storage systems can extend the utilization of PV based distributed energy production systems. The new requirements of current and future electricity networks based on Distributed Energy Resources (DER) in particular for Renewable Energy (REN) lead to system architectures with a combination of technologies to improve performance and efficiency of distributed generation.

Energy storage technologies can deliver stored electricity to an end-user or the electric grid. They can be used as uninterruptible power supply (UPS), or for improving the power quality. Since these energy devices are located usually near the point of use, they are included in the distributed energy resources category. Especially with local energy production such as photovoltaic systems or wind turbines they form a simple hybrid system where it is important to design cost effective optimum system based on the specific needs in on grid and off grid scenarios.

This thesis looks into the typical use-cases and related scenarios in order to categorize the usefulness of electrical storage systems. The main focus is on the combination of photovoltaic electricity production and batteries as a storage system and the different system combinations in on grid and off grid scenarios. The goal is to categorize the results in order to determine the optimal storage size.

The combination with photovoltaic electricity production allows the use of existing data for a wide variety of use-cases. The integration of the electricity output of non-predictable sources requires the balancing of production and load. Understanding the different scenarios and the impact of the storage design parameters will allow for the design of better systems in the context of Distributed Energy Resources.

Table of Contents

List of Tables

List of Figures

Abbreviations

REN	Renewable energy	is energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat.
DER	Distributed energy resources	is a small-scale power generation technologies (typically in the range of 3 kW to 10,000 kW)
PV	Photovoltaic	is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect.
EESS	Electric energy storage system	electric energy is converted into other forms of energy and later converted back to electrical energy.
ESA	Electric storage association	is an international trade association established to foster development and commercialization of energy storage technologies.
UPS	Uninterruptable power supply	provides emergency power to a load when the input power source fails.
CSP	Concentrating solar power	are systems that use mirrors or lenses to concentrate sunlight onto a small area to produce heat which is used to produce electricity similar to conventional power plants.
OTG	Off the grid	are electricity consumer not relying on the public utility grid.
CHP	Combined heat and power	is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat.
AC	Alternating current	the movement of electric charge periodically reverses direction.
DC	Direct current	the unidirectional flow of electric charge.
V2G	Vehicle to grid	is a system in which plug-in electric vehicles sell demand response services by delivering electricity into the grid.[
STC	Standard test conditions	is defined by a module (cell) operating temperature of 25 °C, and incident solar irradiant level of 1000 W/m² and under Air Mass 1.5 spectral distribution.
SOC	State of charge	is the available capacity expressed as a percentage usually based on the capacity of the battery.

1 Introduction

For very long time energy storage has been a part of the traditional energy generation and consumption cycle. Traditionally energy generation has been based on fossil fuel plants and since those plants run most efficiently at full power additional means of storing unused base load power have been devised. Pumped hydropower storage is commonly used to smooth out supply and demand.

1.1 Motivation

As early as around 1900 the need for storage for intermittent energy production has been recognized. An U.S. patent application (Fessenden, 1917) was filed on June 7, 1907, by R. A. Fessenden (granted on November 20, 1917). In it, Fessenden writes:

> *The invention herein described relates to the utilization of intermittent sources of power and more particularly to natural intermittent sources, such as solar radiation and wind power, and has for its object the efficient and practical storage of power so derived.*
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> *It has long been recognized that mankind must, in the near future, be faced by a shortage of power unless some means were devised for storing power derived from the intermittent sources of nature.*
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> *These sources are, however, intermittent and the problem of storing them in a practicable way, i.e., at a cost which should be less than that of direct generation from coal, has for many years engaged the attention of the most eminent engineers, among whom may be mentioned Edison, Lord Kelvin, Ayrton, Perry, and Brush.*

For more than hundred years the centralized production and the establishment of an electric grid infrastructure has been the dominant way of providing electric energy. With the advent of decentralized production and the growing utilization of renewable energy such as solar and wind, a major paradigm shift has begun. Because wind and solar are intermittent energy sources the need of energy storage has become even more important and will be a dominant factor in the development of distributed energy resources.

1.2 Objectives

The role of energy storage will be considered in the specific scenarios commonly encountered when dealing with renewable energy production. Since the photovoltaic (PV) generation is definitely an intermittent energy source since it follows a daily on-off cycle the focus here will be on PV and the associated use-cases.

The main goal is to show that the requirements for the storage system can be derived easily from a simulation for typical scenarios leading to a better understanding of the suitability of storage solutions.

The distributed nature of typical PV power plants leads to additional challenges in the area of electricity grid integration and the utilization of energy storage. Therefore the main focus is on the combination of photovoltaic electricity production and batteries as a storage system and the different system combinations in on grid and off grid scenarios. The economic impact on the electricity production with and without energy storage will be analyzed and presented.

1.3 Citation of main literature

Several books and collection of papers are the main source of information. Since the development of storage solutions often relates to distributed energy resources (DER) related papers and results from research groups provide an excellent insight into the issues.

1.3.1 Books

- “Energy Storage”, Robert A. Huggins, ISBN 978-1-4419-1023-3, Springer-Verlag New York, 2010
- “Large Energy Storage Systems Handbook”, Edited by Frank S. Barnes and Jonah G. Levine, ISBN: 1420086006, CRC Press Taylor & Francis Group, 2011

1.3.2 Research Groups and other Organizations

- CSEM - Center for the Study of Energy Markets (UC ENERGY INSTITUTE)
  (Borenstein, 2008)
- EEG - Energy Economics Group (Vienna University of Technology)
  (Marion Glatz, 2009) (Glatz, 2011) (Rusbeh Rezanio, 2011)
- ESA - Electricity Storage Association
  (ESA, 2011)
- NREL - National Renewable Energy Laboratory
  (HOMER, 2011) (PVWatts, 2011)
- PVGIS - Photovoltaic Geographical Information System
  (PVGIS, 2011)
- DERlab – European Distributed Energy Resources Laboratories e.V.
  (European White Book on Grid-connected Storage - IRES2010, 2010)
- Cellstrom GmbH - Vanadium redox flow battery storage systems
  (GILDEMEISTER energy solutions, 2011) (Cellcube, 2011)

1.4 Structure of work

The main structure of the work presents an introduction into DER systems, related REN systems and electricity storage systems. The scenarios are structured into three areas – grid connected and off-grid systems and micro-grid systems. In order to categorize the use-cases a short overview of intermittent energy generation and the respective demand or load curves are discussed. Existing tools for modeling are introduced and compared to a proposed simple straightforward calculation. Finally the conclusions are presented.

2 Background Information

2.1 The Power Grid

Electricity is generated at a power station or power plant from fossil fuels or renewable resources. Large amounts of power are transferred with electric transmission lines. An interconnected network of transmission lines are commonly referred to as the power grid.

Transmission lines feed into substations where transformers step down the power to lower voltages. From there, power is delivered to individual electric customers by distribution lines.

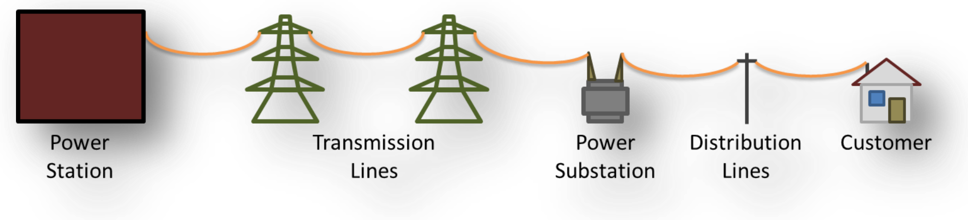


Figure 1: The power grid

The power grid has been built in most countries over the last fifty to hundred years. In some locations this consists of an aging infrastructure, in others the power grid is not even well developed.

In contrast to the centralized large scale power generation, localized domestic power generation has been developed using photovoltaic (PV) generation. The direct conversion of sun light into electricity without moving parts is an intriguing feature of PV electricity generation (see the appendix for a comparison of electricity generation systems).

The simplicity of PV systems and the decentralized deployment have changed the landscape of power grids, utility companies and poses interesting challenges for the stability of the grid and the future development of the electric grid infrastructure.

2.2 Distributed Energy Resources (DER)

From Wikipedia the definition of Distributed Energy Resources (DER) is as follows:

> *Distributed energy resource (DER) systems are small-scale power generation technologies (typically in the range of 3 kW to 10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system.*

The two most interesting sources for DER activities are the DERlab – European Distributed Energy Resources Laboratories e.V. and the Berkely Lab. The Ernest Orlando Lawrence Berkely Nation Laboratory is a U.S. Department of Energy National Laboratory operated by the University of California. The different studies usually define the following characteristics of Distributed Energy Resources:

- Located at or near Point of Use
- Locational Value
- Distribution Voltage

The California Distributed Energy Resources Guide is a public benefit site containing a wealth of information regarding distributed energy resources (DER). This web site cites the drivers for DER as:

- Desire for alternative renewable resources such as solar and wind
- Need for higher quality power in some commercial and industrial facilities as a result of increased use of microelectronic devices
- Remote power applications and the desire to reduce the cost of transmission line upgrades
- Meets requirements for reduced emissions
- Ability to utilize DER's thermal energy at end-user facilities.

The EU program eu-deep is another example of DER related initiatives. A major topic is the Distributed Energy Resources (DER) integration within the electricity grid at distribution level. The project detailed the conditions under which all players will be able to cope with the growing demand for Distributed Energy resources units. The results indicate that there can be a significant added value for the electrical system to better management of peak consumption.

Source: (eu-deep, 2010)

Figure 2: eu-deep DER Integration

DER technologies have several applications such as load reduction, energy independence, standby power, or peak shaving. It is important to note that the use of DER and the issues of grid integration are still viewed as an extension to the current grid.

2.3 Hybrid Renewable Energy Systems

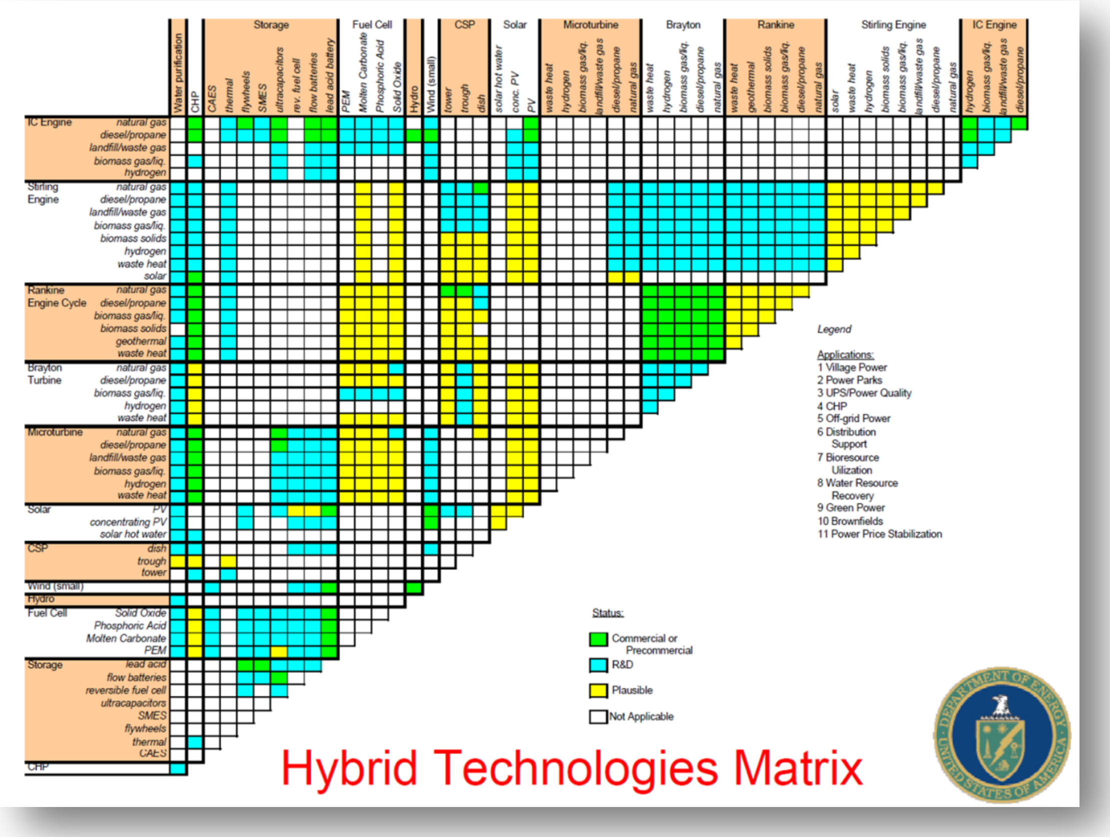
The National Renewable Energy Laboratory (NREL) web site contains a wealth of information on renewable energy. They define Hybrid power systems as a combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device, that when integrated, overcome limitations that may be inherent in either.

Examples of hybrid power systems include:

- Wind generation combined with diesel generation
- Photovoltaic generation combined with battery storage or diesel generation
- Fuel cell generation combined with micro turbine generation.

The synergistic benefits in which the "whole is greater than the sum of its parts" include the system efficiencies which are typically higher than that of the individual technologies used separately. Additionally higher reliability can be accomplished with redundant technologies and/or energy storage.

Those hybrid systems combine a variety of power generation option (wind, solar) with other system components



Source: U.S. DOE Natural Gas / Renewable Energy Workshops (Burch, 2001)

Figure 3: Hybrid Technologies Matrix

The overall management of such a complex system requires much more sophisticated energy management systems and probably new advanced energy management strategies to optimize the wide variety of heat and power generation and consumption options.

However many times the term Hybrid Renewable Energy System refers to simply a combination of PV, wind power, and storage. Sometimes an optional additional power source such as a diesel powered generator or a fuel cell is added.

2.4 Electric Energy Storage Systems

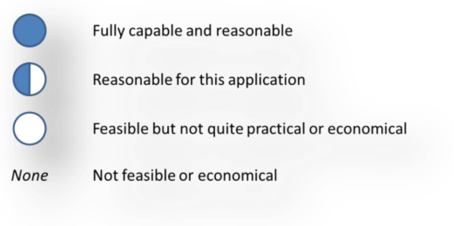
Strictly speaking every fuel – fossil or biomass – is energy storage. Wood logs stored for heating is just energy storage. The stored energy is mostly just converted from the solar energy flow to the earth, converted and stored. The electricity generation is then performed using the conventional steam turbine electricity generation process. To store the electricity the energy has to be transferred to other forms of energy – potential energy, kinetic energy, or chemical energy.

The Electric Energy Storage Systems (EESS) is a kind of energy storage, where electric energy is converted into other forms of energy and later converted back to electrical energy. The best known electrical storage systems are large scale pumped hydro storage systems. However there are many other technology options:

- Pumped Hydro
- High-Speed Flywheels
- Electrochemical Capacitors
- Batteries (Electrochemical Devices)
- Compressed-Air Energy Storage (CAES)

2.4.1 Technology Comparison

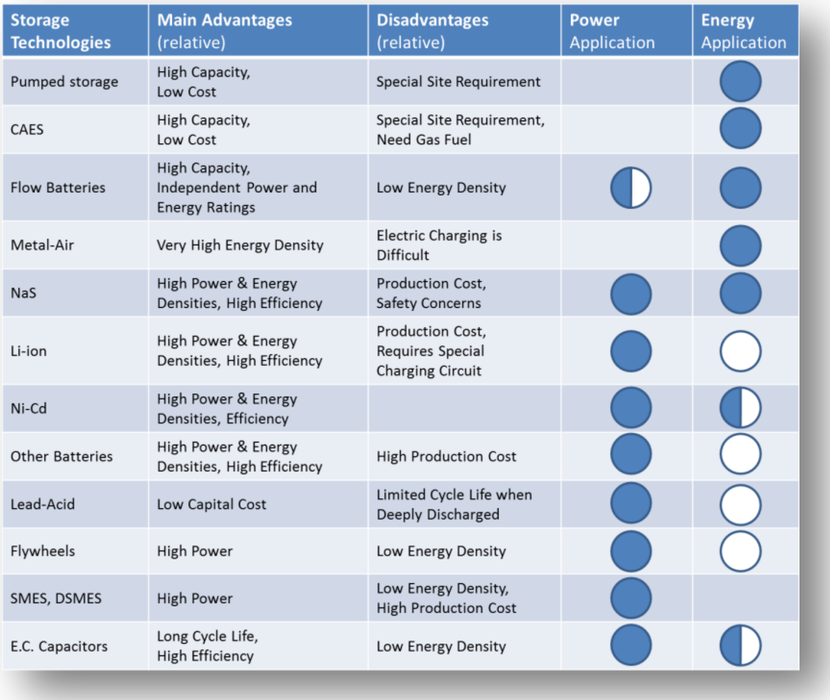
The Electricity Storage Association (ESA) has a good overview of the different storage technologies and their characteristics. It uses the following rating:



●	Fully capable and reasonable
◐	Reasonable for this application
○	Feasible but not quite practical or economical
None	Not feasible or economical

Source: ESA (ESA, 2011)

Figure 4: Technology Rating



Storage Technologies	Main Advantages (relative)	Disadvantages (relative)	Power Application	Energy Application
Pumped storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns	●	●
Li-ion	High Power & Energy Densities, High Efficiency	Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy Density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

Source: ESA (ESA, 2011)

Figure 5: Technology Comparison and Rating

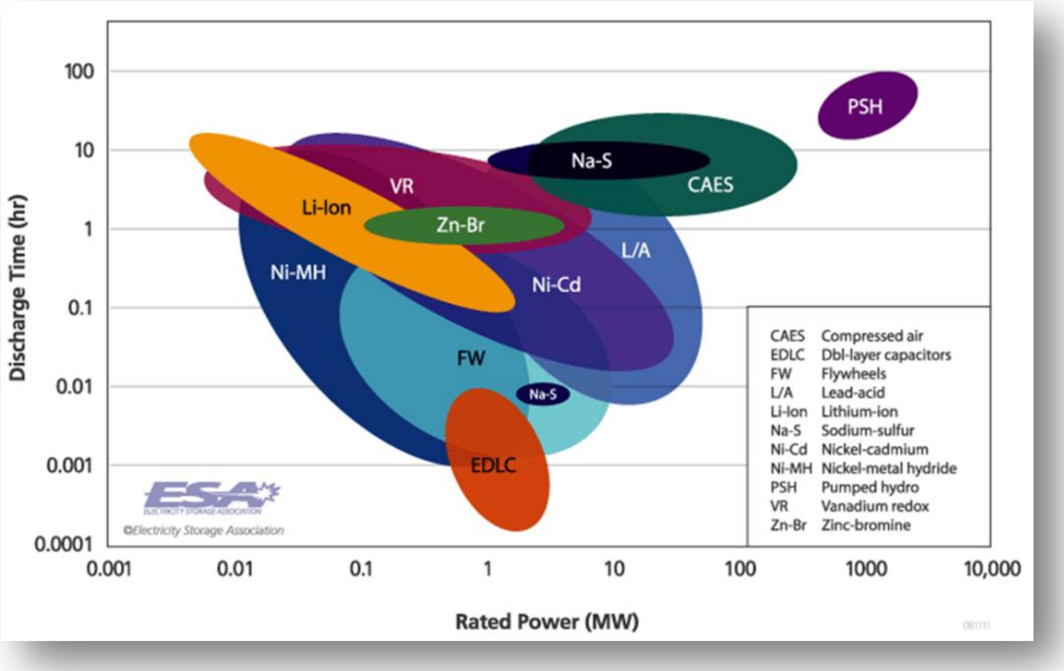
Depending on the actual use the ESA distinguishes three major functional categories:

- Power Quality – energy is applied only for seconds or less
- Bridging Power – energy is used for seconds to minutes to assure continuity
- Energy Management - energy is used to decouple the timing of generation and consumption even being disconnected from the grid for hours

When the energy is supplied for a short period of time the capacity of the storage system is not important. The main requirement is to supply the necessary amount of power to fulfill the demands of the scenario – e.g. flywheels or supercaps. Power management applications use stored energy to ensure continuity, quality and proper frequency of delivered power (ESA, 2011).

For scenarios needing power for a prolonged time the actual stored capacity determines the suitability of the storage systems – e.g. pumped hydro or large batteries. In energy applications – ‘long duration’ storage – use stored energy to decouple the timing of generation and consumption of electric energy (ESA, 2011).

The tables and diagrams presented on the ESA website are considered to be already several years old (2008). However, they are still used as a reference in most publications.



Source: ESA (ESA, 2011)

Figure 6: System Ratings

The energy density of storage technologies has an impact on the physical deployment. For applications such as e-cars a high energy density is obviously preferable – for permanent installations such as domestic ESS or a community ESS the size requirements for different storage technologies are less important.

Efficiency and cycle life are other important parameters to be considered. They have an impact on the overall storage costs. Depending on the actual application the per-cycle cost are even more important. If an ESS is used as an uninterruptible power supply (UPS) and the frequency of a power failure is rather small and the storage system has not many charge/discharge cycles to withstand.

In applications with a frequent charge/discharge cycles combined with possible deep discharge requirements, such as load leveling the storage technology selection has to be done very carefully.

2.4.2 Grid Connection

The grid interconnection is the most significant barrier to the installation of distributed generation technologies. There have been developments of standards (Institute of Electrical and Electronic Engineers IEEE 1547, "Standard for Distributed Resources Interconnected with Electric Power Systems" providing information on the requirements relating to the performance, operation, testing, safety considerations, and maintenance of the grid interconnection.

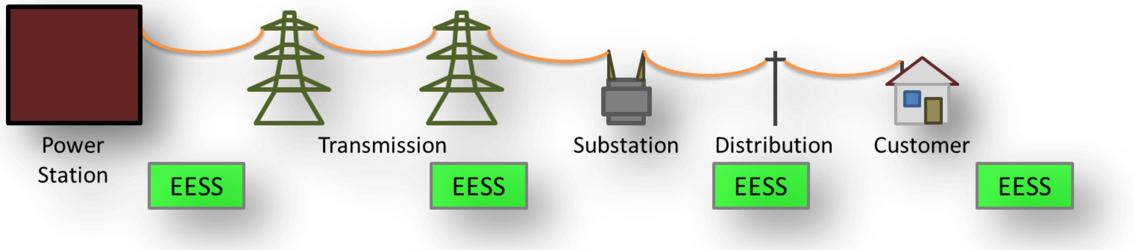


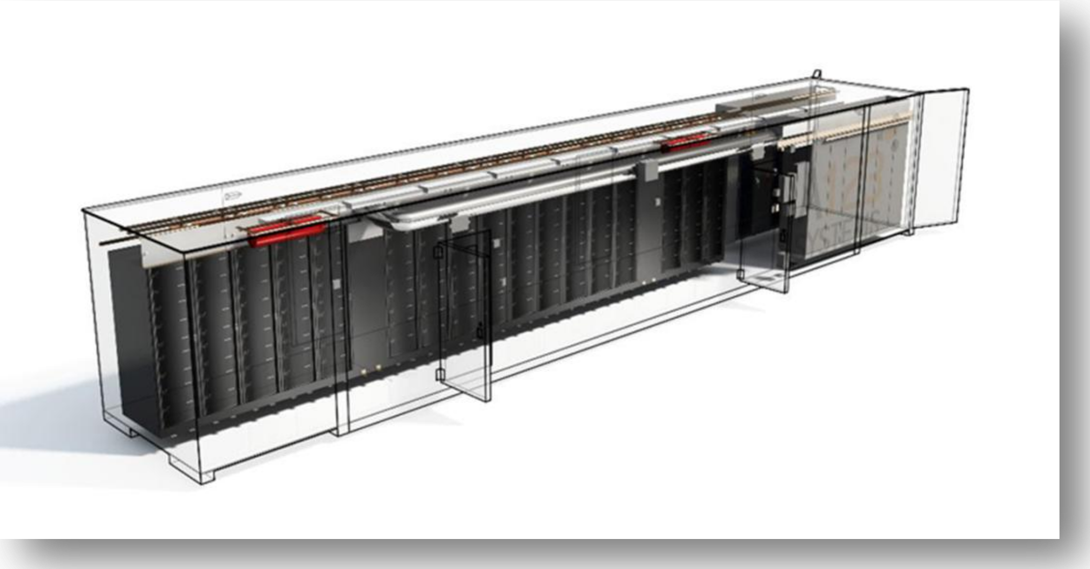
Figure 7: Location of grid-connected EESS

The location of en EESS is related to the distributed nature of the decentralized energy generation and therefore usually located at the distribution level or at the customer premises.

In some applications the storage requirements are somewhat different and the location of the EESS can be even close to a large power station. An example would be a large island with PV generation, wind farms, and other power plants. For such localized power grids a central electric storage could be used. The El Hierro Island (C. Bueno, 2006) can be used as a typical scenario. In order to achieve 100% renewable energy generation based on wind farms a pumped hydro power station with 11.3 MW with a reservoir size of 556.000 m³ is being built. If high power batteries (e.g. flow batteries) are used, roughly 100 container sized units would provide similar storage.

Battery sizes (capacity and power rating) will increase in the next years. This trend can already be seen in the automotive industry where batteries in e-cars are typically sized at 20 kWh or more energy capacity. Large batteries (such as NaS or Flow-Batteries) have already been used in power grid related applications. Larger systems can be created by the combination of a number of smaller systems to provide the needed power and storage capacity. Those systems need special battery management systems (BMS) which will become an integral part of the overall energy management system.

As an example ten container-sized storage systems (A123, 2011) will be used in Chile for a spinning reserve project. The company is even marketing such large systems as a Smart Grid Stabilization System.



Source: A123 Systems (Nanophospate Smart Grid Stabilization System (SGSS), 2011)

Figure 8: Smart Grid Stabilization System (SGSS™)

The energy capacity of such a large system is 500 kWh and can be scaled to larger systems by combining a number of modular units.

Other examples for larger battery systems are Vanadium-Redox flow batteries. The batteries are available in different sizes with a power rating of 10kW or 200kW and an energy capacity of up to 100 kWh for the smaller sizes and up to 400 kWh for the larger system types. The main parameters for the battery size are the power rating and the energy capacity. Since for flow batteries the power rating depends on the number of cells and the energy capacity depends only on the amount of the liquid electrolyte those parameters can be adjusted rather easily.

Source: Cellstrom GmbH

Figure 9: Cellcube Vanadium-Redox Flow Battery 200 kW 400 kWh

Several flow battery units can be combined to provide even larger systems.

Source: Cellstrom GmbH

Figure 10: Cellcube Vanadium-Redox Flow Battery 1MW

The larger systems can be utilized for larger PV generation plants and for large storage applications such as community storage systems.

3 Scenarios

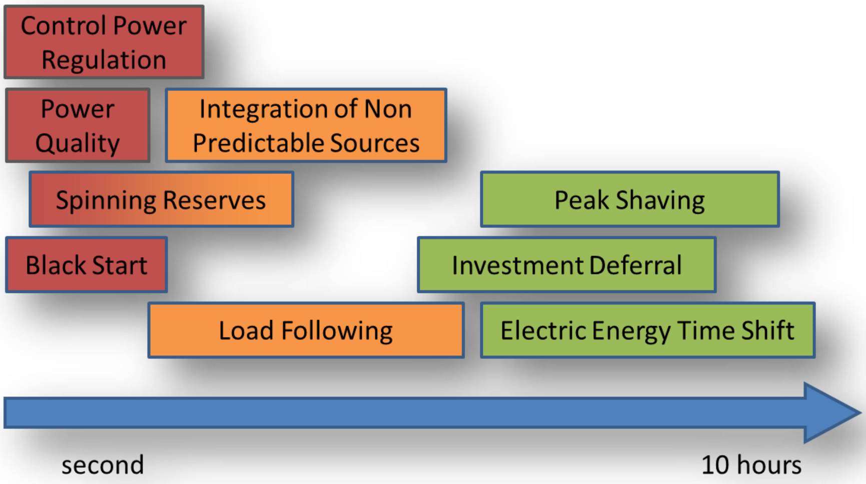
The typical scenarios for the use of storage systems are divided into grid-connected systems and off-grid systems.

3.1 Grid connected systems

From the European White Book on Grid-connected Storage (DERlab, 2010) several scenarios are described:

- Electric Energy Time Shift
- Investment Deferral
- Peak-Shaving
- Load-Following
- Spinning Reserves
- Black Start
- Integration of Non Predictable Sources
- Power Quality

One important requirement is the discharge duration which is quite different in the above mentioned scenarios and can range from sub-seconds to several hours.



Source: based on European White Book on Grid-connected Storage (DERlab, 2010)

Figure 11: EESS Discharge Duration

3.1.1 Electric Energy Time Shift

In this scenario electric energy is purchased and subsequently stored for later reuse during periods where the price is low. The stored electricity is supplied to consumers at a time when the price is high. The different prices on the energy market drive this scenario. With the current energy prices the amount of energy stored has to be rather large. Within the European power grid surplus energy from offshore wind farms can be stored in pumped hydro systems in the Alps or in Norway. Currently overproduction of fossil and nuclear power plants is also transferred to such ‘green’ storage systems for a considerable profit.

3.1.2 Investment Deferral

Overloading of substations, which can appear a few times a year, can be avoided by the use of an EESS supplying the needed power locally. The upgrade of the substation or the maintenance cost due to decreased lifetime of the substation can be avoided.

3.1.3 Peak-Shaving

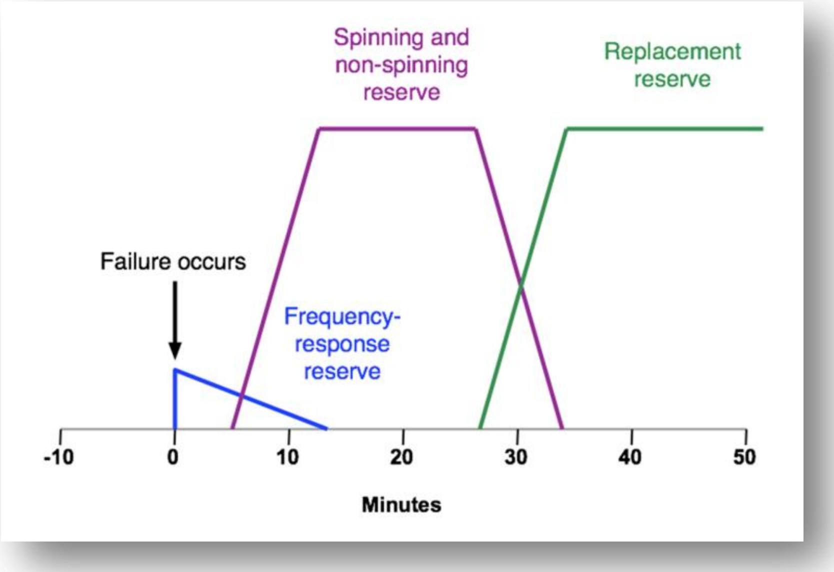
This scenario simply means that the storage system is charged during lower power demand and discharging (locally) when the demand is high. Therefore the high peaks of consumption can be avoided. A good example is the high peak scenario during high noon in California due to excessive cooling energy demand.

3.1.4 Load-Following

Since a storage system can both produce and absorb energy it can be used together with a (local) generator to follow the actual load. This can lead to easing the load balancing requirements in a local grid.

3.1.5 Spinning Reserves

Non-Spinning or supplemental reserve is the extra generating capacity that is currently not connected to the grid, but can be brought online after a short delay. Spinning reserve is the extra generation capacity that is available by increasing the power output of generators that are currently connected to the power system. Most power systems guidelines require a significant fraction of their operating reserve to come from spinning reserve.



Source: (Wikipedia - Reservepower, 2003)

Figure 12: Reserve Power

Spinning reserves has to respond within 10 seconds to maintain system frequency stability. This requires a very fast response from the storage system in combination with usually a very high demand of power.

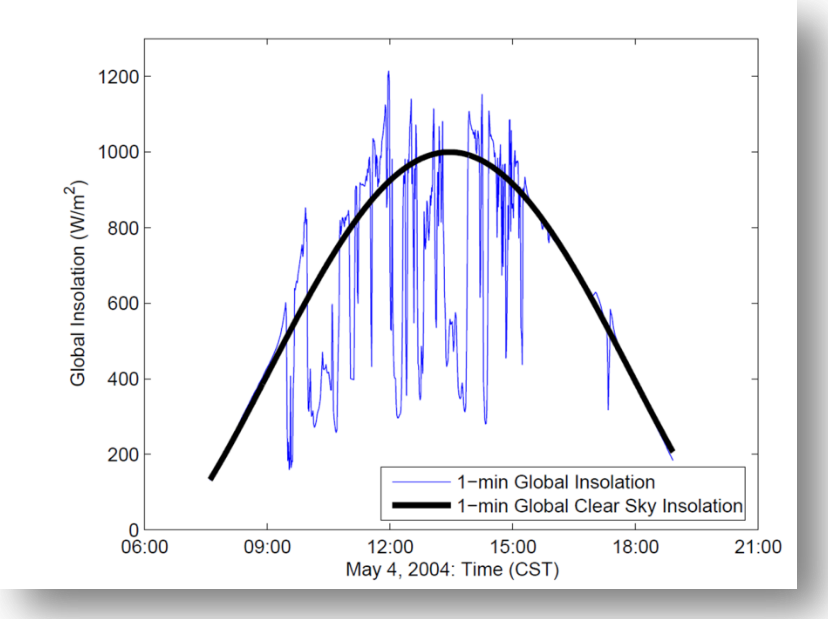
3.1.6 Black Start

The gradual restart of a power grid after a black out commonly require electricity to start-up the generating units. Electric storage systems can provide this electricity.

3.1.7 Integration of Non Predictable Sources

The electricity output of non-predictable (intermittent) generation units, such as photovoltaic (PV), concentrated solar (CSP), or wind is difficult to control. The unbalance between generation and consumption can be remedied by the EESS.

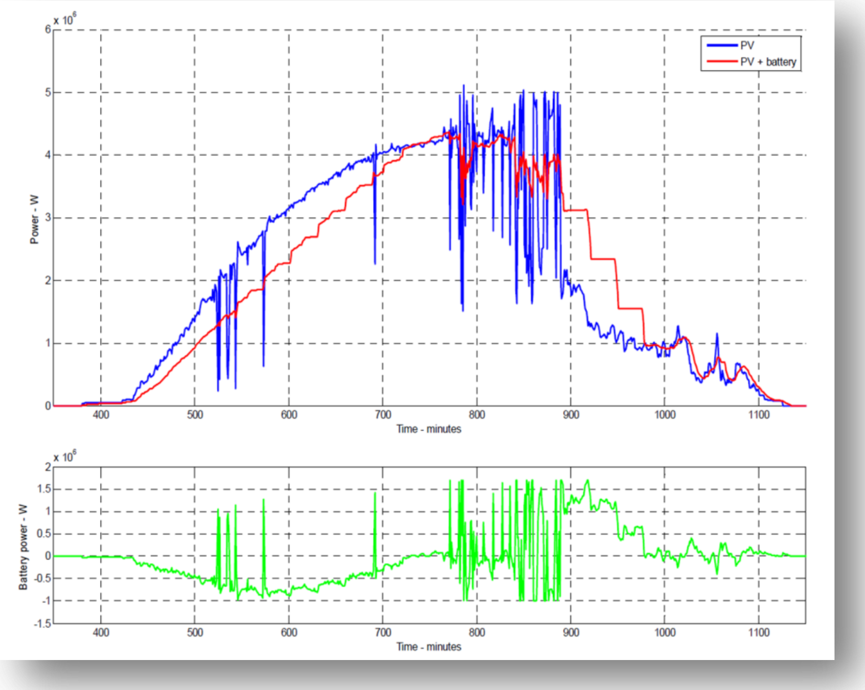
The variability of the actual irradiation, particularly for short periods of time (minutes) can lead to a similar intermittent power production. The upper boundary for the insolation is the clear sky insolation, and the lower boundary is the diffuse insolation.



Source: (Andrew Mills, 2010)

Figure 13: Example of global insolation on a cloudy day

In those scenarios the changes in production can be rather fast (minutes). The resulting unbalance between generation and consumption of electricity has to be regulated by a balancing system.



Source: European White Book on Grid-connected Storage (DERlab, 2010)

Figure 14: Example of smoothing the electricity production

The figure shows the PV production (blue line) and the augmented electricity production by the combination of PV and a storage system (red line). An energy management system has to control the switching between charge and discharge. The scenario is similar to a load following scenario described above.

3.1.8 Power Quality

The storage system can also be used to improve transmission performance by compensating for anomalies and disturbances. This scenario requires fast response (sub-seconds) and a high number of charge-discharge cycles from the EESS.

3.2 Off-grid systems

Usually off-grid systems or off-the-grid (OTG) systems are just on-site electric power generation with local consumption. Typical examples are diesel generators or PV generation in remote areas such as the alpine hut ‘Schiestl-Haus’ (Bründlinger, 2005):

Source: (Datei:Schiestlhaus Jul2007.jpg, 2007)

Figure 15: PV Generation for a typical off-grid scenario

The electricity is produced by a 7.5 kW PV installation integrated in the facade and a vegetable oil CHP plant. The whole electricity supply is designed as an AC Hybrid System. Other typical examples are power supplies for telecommunication equipment such as transmitters or relay stations.

A combination of different power generation systems can also be found in the case of grid-connected systems (or better temporarily connected systems) and is actually called a microgrid system.

3.3 Microgrid Systems

A microgrid (Wikipedia - microgrid, 2011) is a localized grouping of electricity generation, energy storage, and loads that normally operate connected to a traditional centralized grid. Those systems can also operate in a disconnected mode. Locally they are just a small scale version of a traditional centralized grid. The feature of a microgrid to separate and isolate itself from the grid and to automatically reconnect itself (and resynchronize with the grid) requires sophisticated energy management and control solutions.

Since the majority of microgrid solution relies on photovoltaic electricity generation the combination of PV and an EESS is the main focus in this study.

3.4 PV Generation and Storage

The typical grid-connected PV system has only a few components:

- PV Modules
- Inverter
- Power Meter

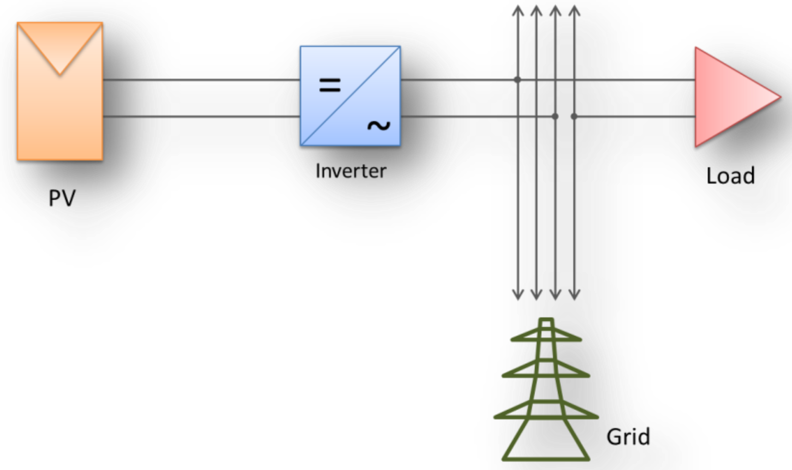


Figure 16: PV Generation

Grid-connected PV systems are designed to operate in parallel with the electric utility grid. The inverter is the main component converting the DC power generated by the PV modules into AC power consistent with the voltage and power quality requirements of the power grid. The AC power can then be used locally or fed into the grid.

The addition of an electric storage system (usually a battery) into the grid-connected PV system can be implemented in two ways:

- DC Bus Coupling
- AC Bus Coupling

In the case of DC coupling the battery is connected to the DC output of the PV array. If there are different DC levels for PV and the battery a DC/DC converter is employed. The DC Bus is then connected to the inverter to transfer the DC output to AC output. The use of a higher voltage DC bus (e.g. 400 V) is also used in the automotive industry, further fostering the development of DC/DC converter systems and bidirectional chargers/inverters.

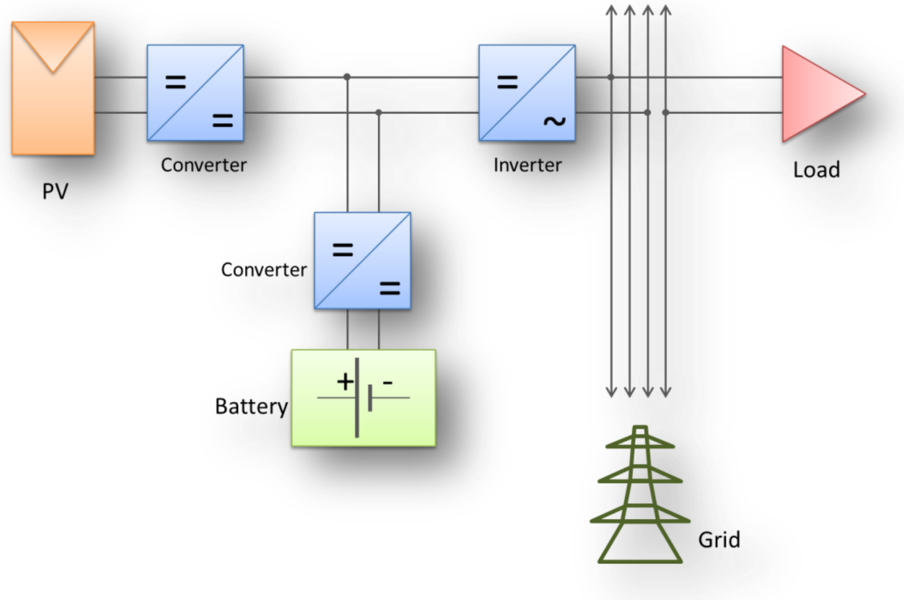


Figure 17: DC Bus coupling

Note that here inverter could operate in bidirectional fashion in order to allow loading the battery from the grid which is more likely an option for grid-stabilization then vehicle-to-grid (V2G) which is sometimes seen as a viable option in the future.

The second alternative implementation is the formation of an AC bus by simply using a bidirectional charger at the storage unit. Also here a supervisory energy management is needed to control the flow of energy between the power generation, the electrical storage, the domestic load and the utility grid.

When considering the metering requirements this might be a simpler solution in order to allow for the independent metering of PV generation, load consumption, and feed-in to the grid.

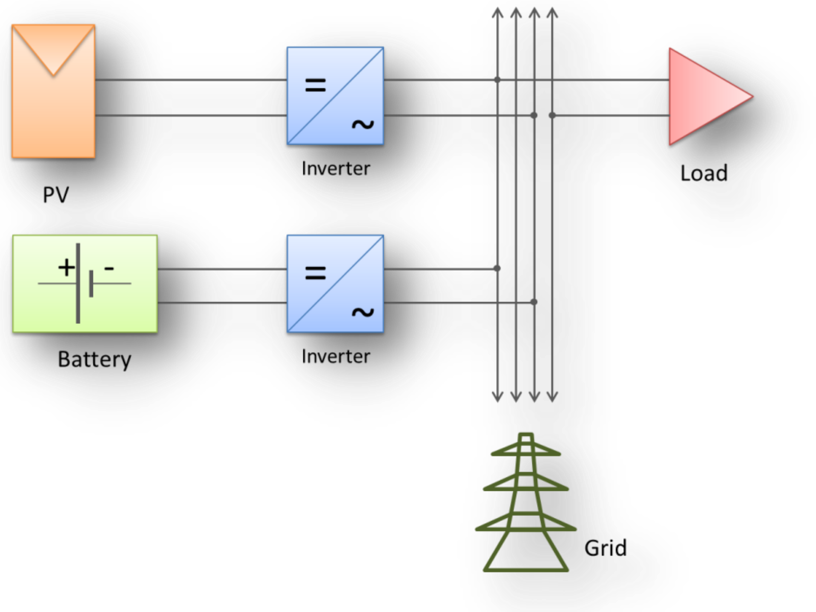


Figure 18: AC Bus coupling

Again a quick comment – if the reimbursement for provided energy at peak load time is considerable higher than the cost of electricity during charging periods (the typical scenario for the integration of the storage facility in the car to the grid) it will be cheaper and simpler to use larger permanent installations of electric storage systems.

4 Specific Scenario

4.1 Overview

Out of the many different use cases for Electric Energy Storage Systems (EESS) in the context of distributed generation is the combination of PV generation and a battery. The variation of systems is still considerable – small domestic systems, larger community bases systems, to even larger sizes.

Since the domestic installed PV systems, which can be commonly found in Europe (especially in southern Germany) are probably the smallest system size to be considered. For the combination of a number of small domestic PV generation units for a larger community owned facility a larger sized community energy system could be envisioned. From Wikipedia – “A sustainable community energy system is an integrated approach to supplying a local community with its energy requirements from renewable energy or high-efficiency co-generation energy sources. The approach can be seen as a development of the distributed generation concept.”. Such systems are well established for heating purposes with the implementation of district heating systems – but for energy production this is less common.

4.1.1 Power Generation

The power generation in those specific use-cases is PV based. The size of the typical PV installation for a household is between 3 kW_p and 5 kW_p sometimes larger. Since Germany, due to their favorable FIT system, is the country with a high penetration of domestic PV use the statistics for PV installations is very interesting.

In marketing studies (IHS, 2011) the PV installations in the world's major solar markets it can be seen that Germany is still the leader; but the Asian and the US market is considered to grow more during the next years to come.

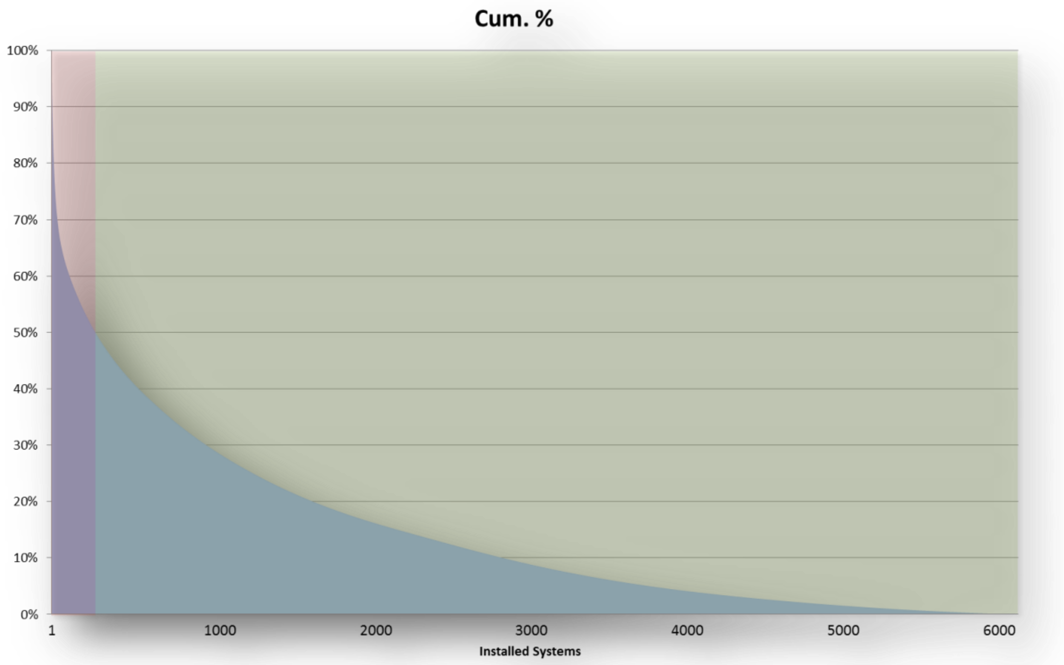
	2010	2011
Belgium	390	488
Bulgaria	20	70
China	400	700
Czech Republic	1,331	350
France	520	550
Germany	6,727	9,400
Greece	120	235
Italy	2,850	3,900
Japan	950	1,100
South Korea	145	170
Canada (Ontario)	213	730
Spain	250	345
United Kingdom	95	350
USA	937	2,073
Rest of World	798	1,779
Total	**15,747**	**22,239**

Source: (Photovoltaic Market in Europe to Account for 70 Percent of World Total in 2011 , 2011)

Figure 19: PV Installations (MW)

Since in most publications only the largest installations are mentioned, it is difficult to get an overview of the size distribution. However, from online portals showing the connected systems (and their production) such as the monitoring portal from SMA Technology AG (SMA Solar Technology AG, 2011) a list of installed systems can be accessed. Again PV plants installed in Germany dominate the list with almost 6500 sites. Since overall roughly 250.000 PV sites are operated in Germany alone the size statistics with a sample of 6500 seems sufficient.

In order to understand the size distribution of the installed systems the cumulative percentage of the listed photovoltaic installations in Germany are plotted against the number of the systems. The resulting distribution (Long Tail, 2011) or power law distribution shows the contribution of the different size of installations to the overall amount of photovoltaic generation capacity.



Source: Calculation based on data from SMA (SMA Solar Technology AG, 2011)

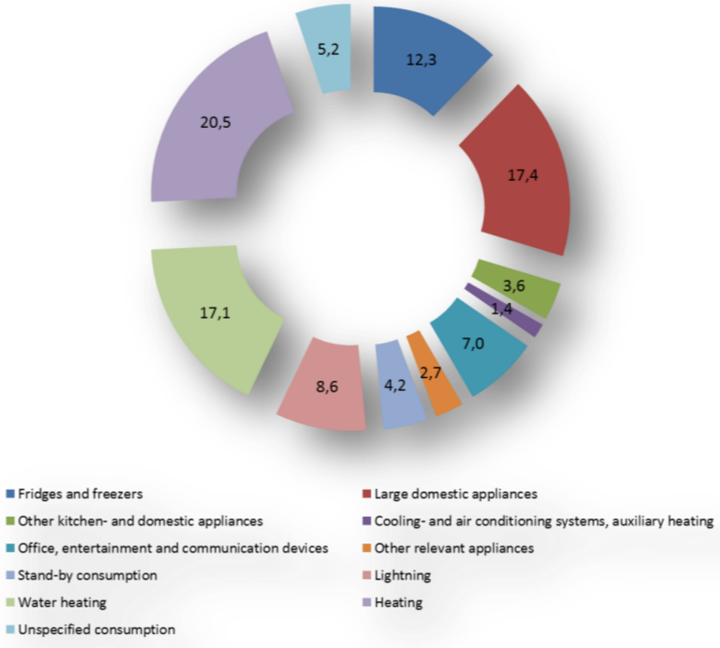
Figure 20: PV Generation Size Distribution - Long Tail

Note that roughly the first 300 installations account for 50% of the cumulative production. The sum of all remaining smaller system adds up to the remaining 50%. This is similar to the Pareto Principle also known as the 80-20 rule (80% of the sales come from 20% of the clients), however in this example only 50% of the production is covered by the first 20%. This means that most installations are rather smaller size deployments of PV most likely in single household domestic scenarios.

Since the domestic use of PV is such a large fraction of the installations it is considered the main use-case for this study. Since the basic assumptions and calculations can be scaled even to larger (e.g. community sized) systems the single household is the focusing point here.

4.1.2 Power Demand

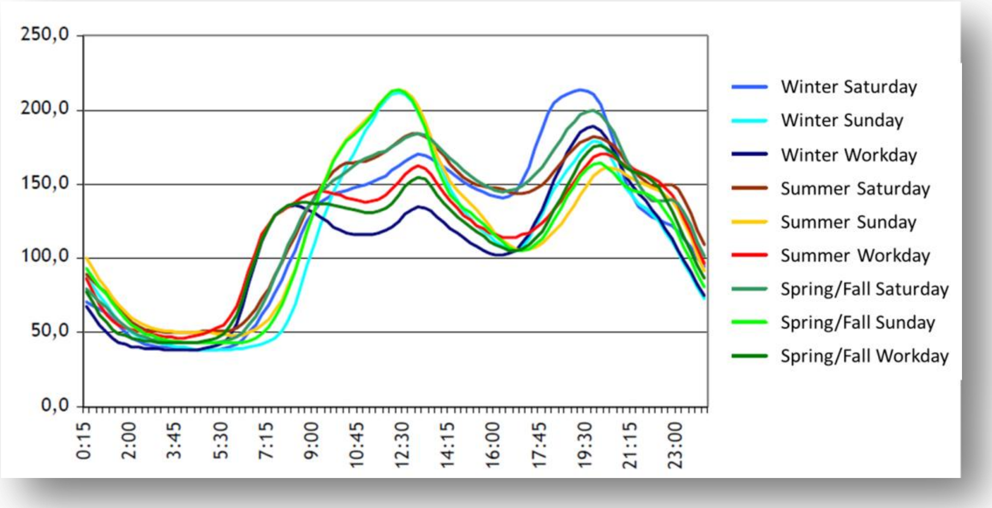
The power demand of households is also well studied. The statistical data are available for many countries and locations. The categorization of electricity use in households is a good example:



Source: (Statistics Austria, 2009)

Figure 21: Average Energy Consumption of Households

Similar data are also gathered by the utility companies – they usually operate based on average consumption defined in standardized load curves. A typical load profile for households lists the load for every hour (or every 15 min) for a typical day of the year. Usually the data are available for weekdays, Saturdays, or Sunday in the different seasons of the year (winter, spring, summer and fall).

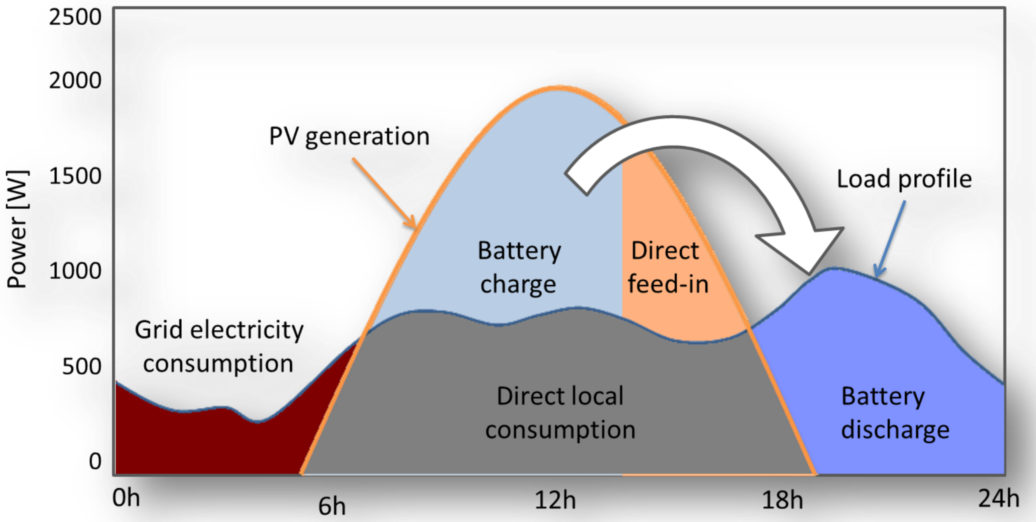


Source: (Ing. Otto Kalab, Wirtschaftskammer OÖ, 2011)

Figure 22: Load Profile for Households

The actual load data used in this study are described in more detail in the chapter on simulation.

The energy management strategy in the domestic household use-case is rather simple – the battery will be charged when the PV generation is larger than the load and used in the evening when PV generation is not available anymore.

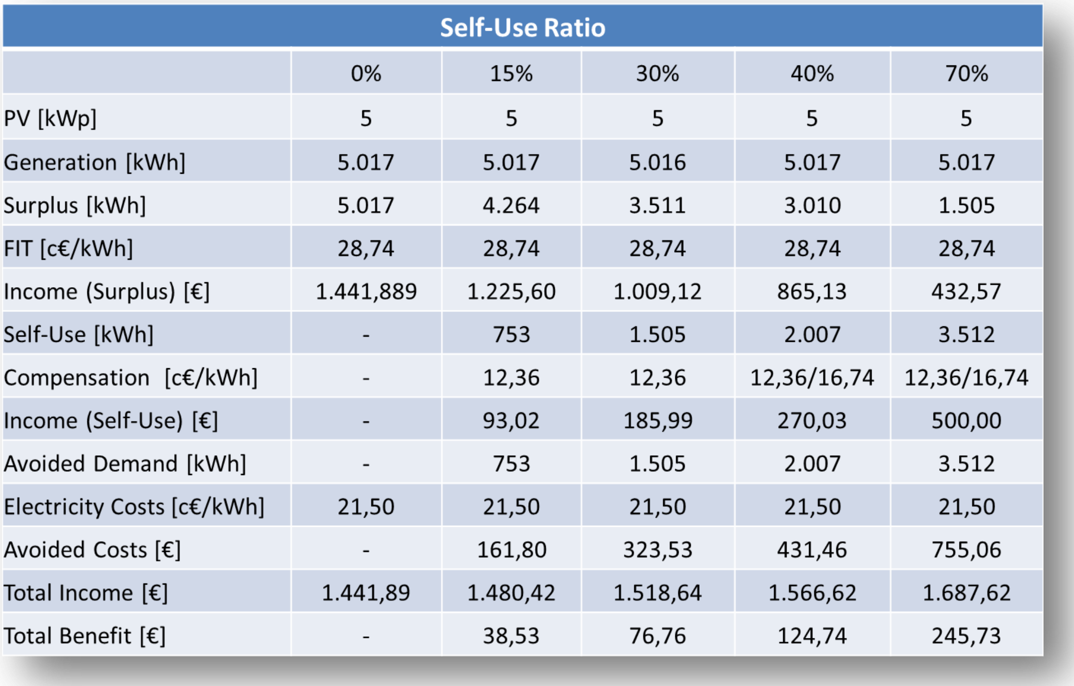


Source: based on (Martin Braun, 2009)

Figure 23: Energy Management Strategy

In Germany the Renewable Energy Act - Erneuerbare-Energien-Gesetz (EEG) - includes an additional incentive for the energy used locally at the production site. Section 33 states that operators of solar power plants up to 500 kWp which are in operation by January 2012 may consume their own production in full or part and will receive an additional remuneration. The portion of the total solar power production not consumed by the operator can be fed into the public grid at the regular feed-in tariff. A precondition for recompense for self-consumption is that the power is used in the immediate vicinity of the plant operator or of third parties and the amount of power consumed can be verified.

The examples shown here indicate the profit from own power consumption (self-use). Based on a plant size of 5 kWp and an annual yield of 5017 kWh the self-consumption rates of 15%, 30%, 70% can be compared to full grid feed-in.



Self-Use Ratio					
	0%	15%	30%	40%	70%
PV [kWp]	5	5	5	5	5
Generation [kWh]	5.017	5.017	5.016	5.017	5.017
Surplus [kWh]	5.017	4.264	3.511	3.010	1.505
FIT [c€/kWh]	28,74	28,74	28,74	28,74	28,74
Income (Surplus) [€]	1.441,889	1.225,60	1.009,12	865,13	432,57
Self-Use [kWh]	-	753	1.505	2.007	3.512
Compensation [c€/kWh]	-	12,36	12,36	12,36/16,74	12,36/16,74
Income (Self-Use) [€]	-	93,02	185,99	270,03	500,00
Avoided Demand [kWh]	-	753	1.505	2.007	3.512
Electricity Costs [c€/kWh]	21,50	21,50	21,50	21,50	21,50
Avoided Costs [€]	-	161,80	323,53	431,46	755,06
Total Income [€]	1.441,89	1.480,42	1.518,64	1.566,62	1.687,62
Total Benefit [€]	-	38,53	76,76	124,74	245,73

Source: (Eigenverbrauch, 2011)

Table 1: Self-Use Compensation

Since the personal consumption behavior is difficult to influence, it seems that such a compensation scheme would favor smaller PV systems because of the higher self-use ratio. The simulation presented here is using a similar approach based on 15 min data for production and consumption.

4.2 Larger Systems

For the combination of several households into a collection of electricity consumers the basic use-case from above is still valid. The load distribution will be more smooth and closer to the standardized load profile. The PV generation will still be strongly intermittent and non-predictable due to the local weather conditions. The installation of larger Community Energy Systems (CES) systems will require larger batteries but the actual energy management system could be centralized into the CES. The load data could be collected based on the same technologies used in the smart grid initiative.

5 Simulation

The discussion of use-cases for the energy storage system supported photovoltaic power plants has shown a wide variety of application scenarios. The next chapter presents the actual simulation of such a scenario using a simple Microsoft Excel spreadsheet application.

5.1 Overview

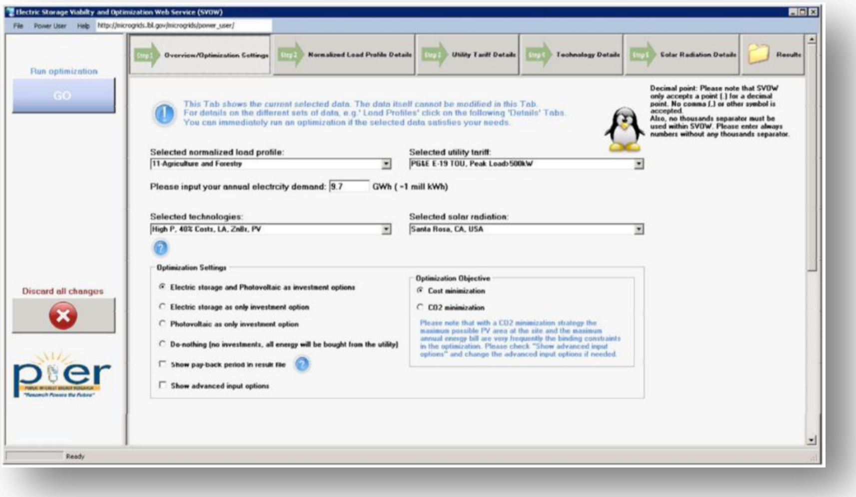
There are many studies on the simulation of distributed energy generation and use. Several tools for the calculation and optimization of such systems are available. Where many tools are focusing on PV generation and economic validation some are considering complete scenarios with integrated battery systems or hybrid generation using wind or diesel generators in addition to PV. The tools offer different resolution of data – hourly, daily etc. Some calculations have been even performed based on minute load profile data.

5.2 Tools

Two very interesting tools which take battery and PV generation into account are SVOW and HOMER.

5.2.1 SVOW

The Storage Viability and Optimization Website (SVOW) (Stadler, 2011) tries to provide basic guidance on whether available storage technologies, PV or combinations of these technologies could be a viable option. However, the basic setup of this tool is mainly targeted at the non-residential sector in the US.



This Tab shows the current selected data. The data itself cannot be modified in this Tab.
For details on the different sets of data, e.g.' Load Profiles' click on the following 'Details' Tabs.
You can immediately run an optimization if the selected data satisfies your needs.

Decimal point: Please note that SVOW only accepts a point (.) for a decimal point. No comma (,) or other symbol is accepted.
Also, no thousands separater must be used within SVOW. Please enter always numbers without any thousands separator.

Selected normalized load profile: 11-Agriculture and Forestry

Selected utility tariff: PG&E E-19 TOU, Peak Load>500kW

Please input your annual electrcity demand: 9.7 GWh (~1 mill kWh)

Selected technologies: High P, 40% Costs, LA, ZnBr, PV

Selected solar radiation: Santa Rosa, CA, USA

Optimization Settings
- ● Electric storage and Photovoltaic as investment options
- ○ Electric storage as only investment option
- ○ Photovoltaic as only investment option
- ○ Do-nothing (no investments, all energy will be bought from the utility)
- ☐ Show pay-back period in result file
- ☐ Show advanced input options

Optimization Objective
- ● Cost minimization
- ○ CO2 minimization

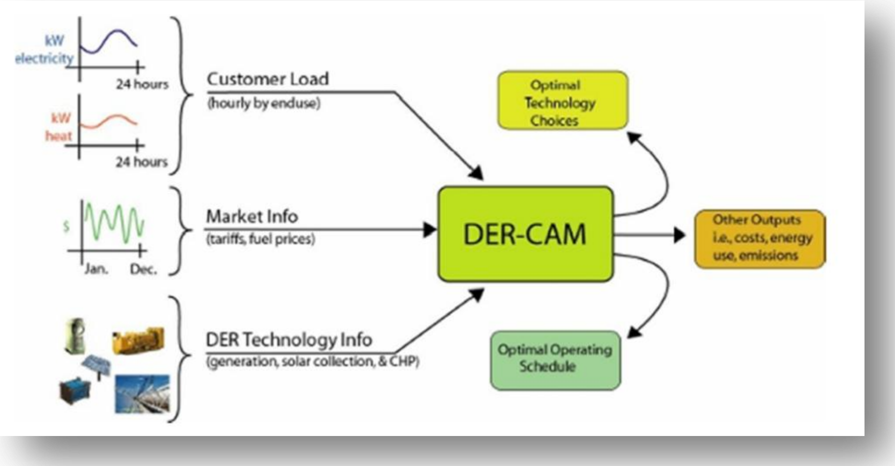
Please note that with a CO2 minimization strategy the maximum possible PV area at the site and the maximum annual energy bill are very frequently the binding constraints in the optimization. Please check "Show advanced input options" and change the advanced input options if needed.

Source: (SVOW) (Stadler, 2011)

Figure 24: SVOW Application

SVOW is a free service that includes 20 standard load profiles for non-residential energy users. The datasets contain technology parameters for the batteries and PV, tariffs for medium and large commercial/industrial customers in selected US territories. Some parameters (load profile) can be modified by the user.

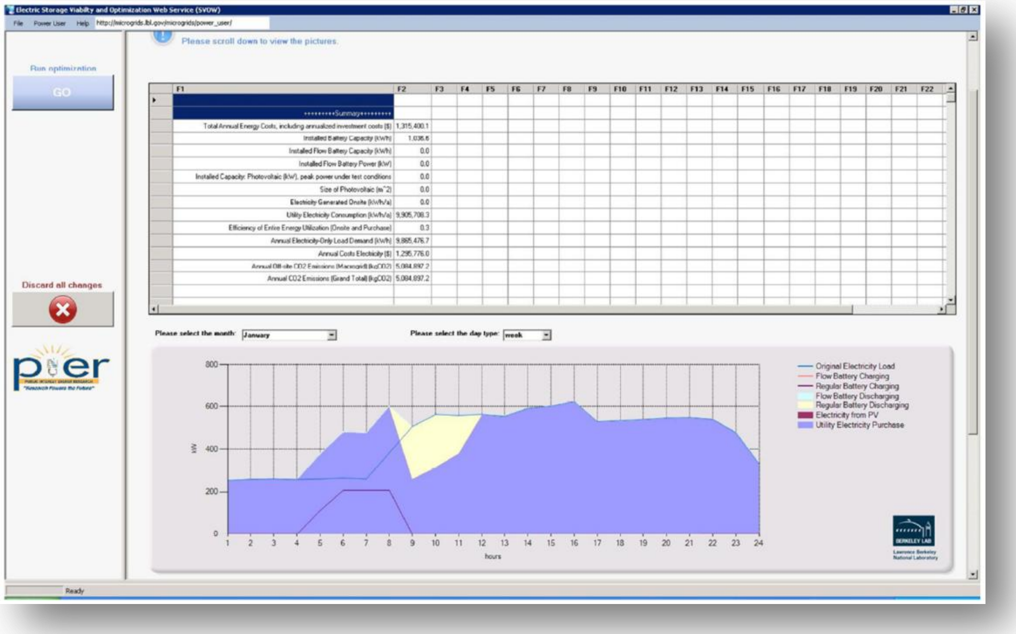
The actual calculation is based on the Distributed Energy Resources Customer Adoption Model (DER-CAM) (Michael Stadler, 2011), which is a mixed-integer linear program (MILP) written and executed in the General Algebraic Modeling System (GAMS) running as a service on the SVOW website.



Source: (DER-CAM) (Michael Stadler, 2011),

Figure 25: DER-CAM

After running the simulation several output parameters are shown:



Please scroll down to view the pictures.

F1	F2
+++++++++Summary+++++++++	
Total Annual Energy Costs, including annualized investment costs ($)	1,315,400.1
Installed Battery Capacity (kWh)	1,036.6
Installed Flow Battery Capacity (kWh)	0.0
Installed Flow Battery Power (kW)	0.0
Installed Capacity: Photovoltaic (kW), peak power under test conditions	0.0
Size of Photovoltaic (m^2)	0.0
Electricity Generated Onsite (kWh/a)	0.0
Utility Electricity Consumption (kWh/a)	9,905,708.3
Efficiency of Entire Energy Utilization (Onsite and Purchase)	0.3
Annual Electricity-Only Load Demand (kWh)	9,865,476.7
Annual Costs Electricity ($)	1,295,776.0
Annual Off-site CO2 Emissions (Macrogrid) (kgCO2)	5,084,897.2
Annual CO2 Emissions (Grand Total) (kgCO2)	5,084,897.2

Please select the month: January

Please select the day type: week

Source: (SVOW) (Stadler, 2011)

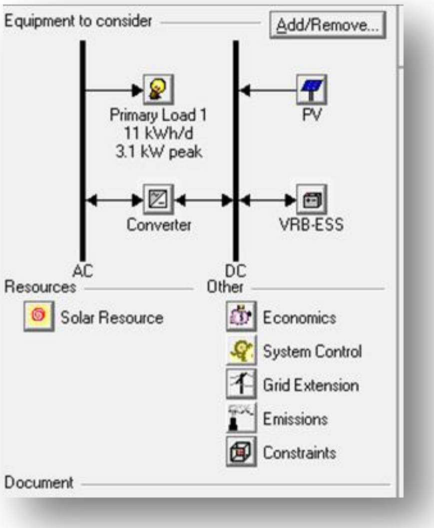
Figure 26: SVOW Simulation results

- Total Annual Energy Costs ($)
- Payback period of investments (years)
- Installed Battery Capacity (kWh)
- Installed Flow Battery Capacity (kWh)
- Installed Flow Battery Power (kW)
- Installed Capacity: Photovoltaic (kWp)
- Size of Photovoltaic (m^2)
- Electricity Generated Onsite (kWh/a)
- Utility Electricity Consumption (kWh/a)
- Efficiency of Entire Energy Utilization (Onsite and Purchase)
- Annual Electricity-Only Load Demand (kWh)
- Annual Costs Electricity ($)
- Annual CO2 Emissions (Grand Total) (kgCO2)

The graph shows the hourly optimal schedule for week-, peak-, and weekend days.

5.2.2 HOMER

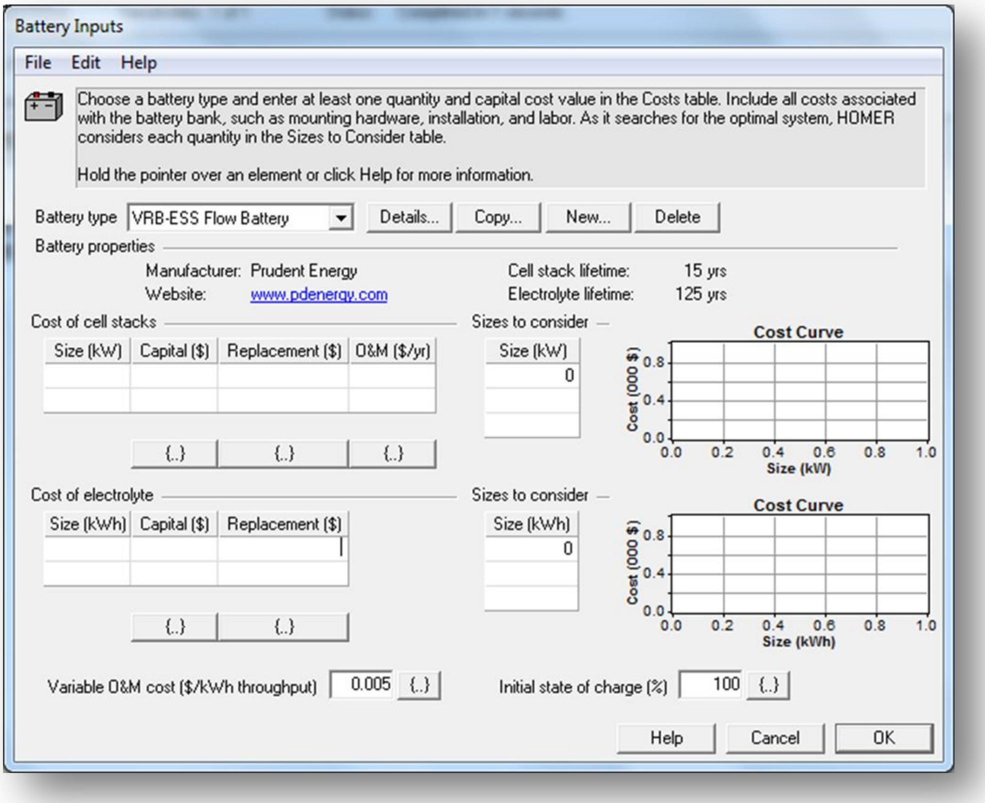
The HOMER energy modeling software (HOMER - Energy Modeling Software for Hybrid Renewable Energy Systems, 2011) is a tool for designing and analyzing hybrid power systems, which contain a mix of conventional generators, cogeneration, wind turbines, solar photovoltaic, hydropower, batteries, fuel cells, hydropower, biomass and other inputs. It simulates different system configurations with pre-selected components, optimizes for lifecycle cost, and generates results of sensitivity analyses.



Source: (HOMER - Energy Modeling Software for Hybrid Renewable Energy Systems, 2011)

Figure 27: HOMER Configuration Setup

Operation in HOMER is simulated by calculating energy balances for each hour in a year to minimize total lifecycle cost. The battery model in HOMER is rather sophisticated compared to other tools.



Choose a battery type and enter at least one quantity and capital cost value in the Costs table. Include all costs associated with the battery bank, such as mounting hardware, installation, and labor. As it searches for the optimal system, HOMER considers each quantity in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Battery type: VRB-ESS Flow Battery

Battery properties

Manufacturer: Prudent Energy
Website: www.pdenergy.com
Cell stack lifetime: 15 yrs
Electrolyte lifetime: 125 yrs

Cost of cell stacks

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)

Sizes to consider

Size (kW)
0

Cost of electrolyte

Size (kWh)	Capital ($)	Replacement ($)

Sizes to consider

Size (kWh)
0

Variable O&M cost ($/kWh throughput): 0.005

Initial state of charge (%): 100

Source: (HOMER - Energy Modeling Software for Hybrid Renewable Energy Systems, 2011)

Figure 28: HOMER Battery Data Input

One drawback seems to be that the simulation always starts with a full battery. This leads to different data since the value at the beginning of January should reflect the battery state at the end of the year.

Different to the SVOW calculations, HOMER does not capture the effect of tariffs. For most other data the HOMER simulation package results in nice reports and has extensive input options.

5.3 Simple Microsoft Excel based tool

Many simulations – especially for simple PV system evaluation are based on Microsoft Excel. Also in this study a simple Microsoft Excel spreadsheet is used to simulate the scenarios using a photovoltaic generation facility and an optional battery storage system. The main goal was to have a quick and simple solution to gather insight into the usefulness of an electrical storage system.

The typical system consists of the PV generation (a collection of PV modules, cables etc.), converters to an internal DC-bus, the battery, and an inverter to convert DC to AC current. The system is considered grid connected.

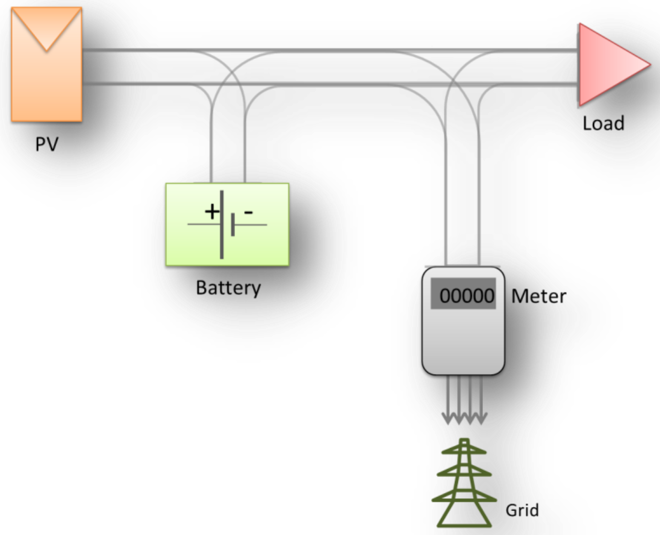


Figure 29: System components of typical PV generation system

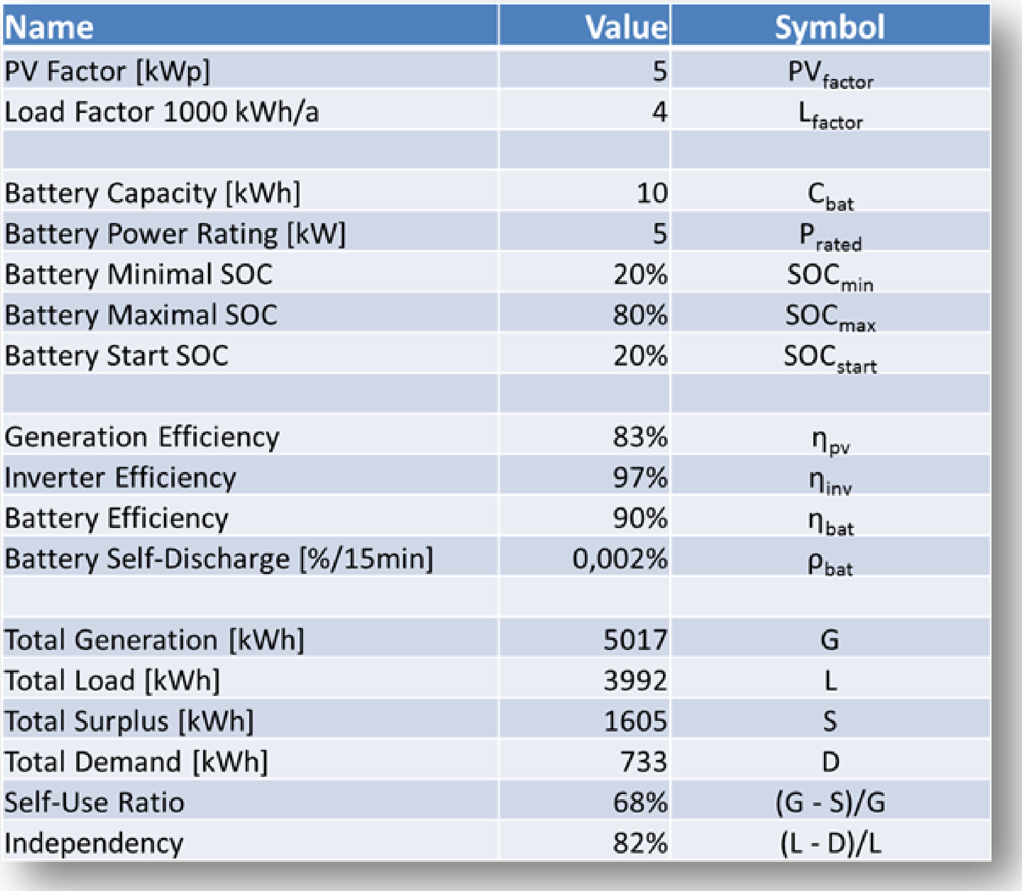
The actual systems for metering are not relevant for the simulation. There could be even more metering systems (PV generation metering) or bidirectional meters at the grid connection point.

5.3.1 Model Input Data

In some studies very detailed load curves (1 min resolution) have been used. The different granularity of load data and PV generation data used throughout the simulations tools and different studies makes it difficult to compare the results. The use of stochastic methods (randomizing generation and/or loads) adds to the complexity.

In the Microsoft Excel based tool the datasets are based on 15 min data for every day in the year. The reasoning is that with the increasing use of smart metering, where data are typically collected in 15 min intervals, will lead to useful input data. When the data are available in different time intervals they have to be converted. The complete set of 365 days times 96 daily 15 min intervals (35040 cells) for PV generation and load profile data is the main input. For a more detailed description of the simulation tool see the appendix chapter 8.3.

The basic assumptions are that a just few input parameters are sufficient to define the conditions for the actual simulation.



Name	Value	Symbol
PV Factor [kWp]	5	PV_{factor}
Load Factor 1000 kWh/a	4	L_{factor}
Battery Capacity [kWh]	10	C_{bat}
Battery Power Rating [kW]	5	P_{rated}
Battery Minimal SOC	20%	SOC_{min}
Battery Maximal SOC	80%	SOC_{max}
Battery Start SOC	20%	SOC_{start}
Generation Efficiency	83%	η_{pv}
Inverter Efficiency	97%	η_{inv}
Battery Efficiency	90%	η_{bat}
Battery Self-Discharge [%/15min]	0,002%	ρ_{bat}
Total Generation [kWh]	5017	G
Total Load [kWh]	3992	L
Total Surplus [kWh]	1605	S
Total Demand [kWh]	733	D
Self-Use Ratio	68%	(G - S)/G
Independency	82%	(L - D)/L

Table 2: Basic input output fields

5.3.1.1 Scaling Factors

The PV Factor is defining the size of the photovoltaic generation. The production data (normalized for 1 kWp) from the PVGIS website is multiplied by the PV factor to get the actual generation value.

The load factor is used to scale the load data (normalized for a yearly load of 1000 kWh) to get the actual load for the simulation.

5.3.1.2 Battery Data

The battery data used in the simulation are just the capacity (kWh), the power rating (max. kW in charging/discharging). Since for many battery technologies there is a limit in the useful range of the state of charge (SOC) this can be added as an input further limiting the capacity of the storage. The battery start SOC allows determining the charging state of the battery at the beginning of the calculation. Since the simulation covers a complete year (365 days) ideally the SOC of the battery at the beginning and the end of the simulated time frame should be the same (e.g. for smaller batteries this would be the minimum SOC since the battery storage is empty at the beginning of the year – 1st of January).

5.3.1.3 Efficiency Data

Several efficiency factors are used to further control the calculation. Depending on the actual systems used those factors have to be determined based on the available data sheets (PV, inverter, battery). For the battery the self-discharge is also an important input parameter since even if the energy storage system is not used the state of charge diminishes due to the self-discharge rate.

5.3.2 Energy Flow

The simulation simply takes the PV generation, the load, and the stored energy in the battery to decide on the actual energy transfer.

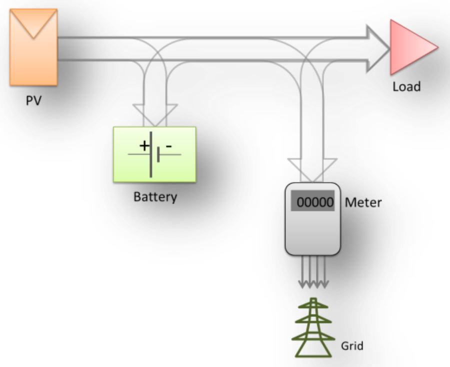


Figure 30: Energy flow

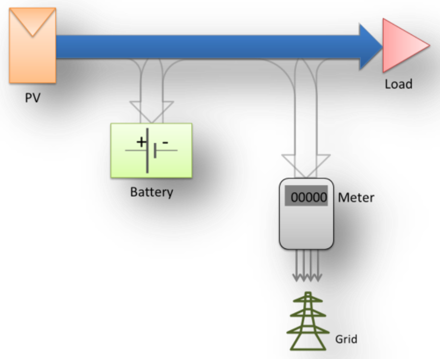


Figure 31: Energy flow self-use

If the generated energy cannot be utilized it will be transferred to the grid as a surplus. If the energy balance leads to a demand which cannot be fulfilled by the generation and the electric storage system, the demand is satisfied from the grid.

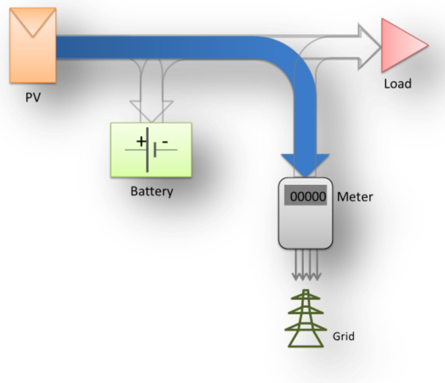


Figure 32: Energy flow surplus

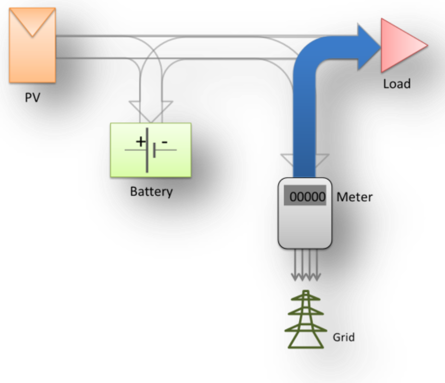


Figure 33: Energy flow demand

The battery storage system is used within the boundaries set by the global input parameter. The minimum and the maximum state of charge (SOC_{min}, SOC_{max}) determine if the battery can still be charged or discharged.

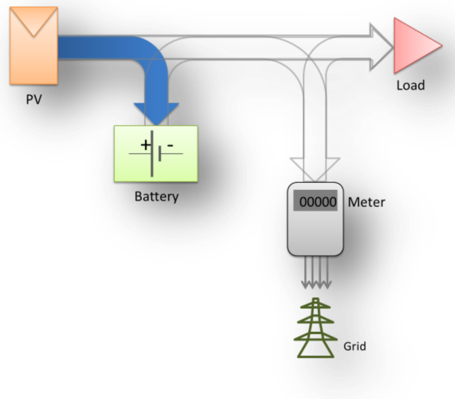


Figure 34: Energy flow charge

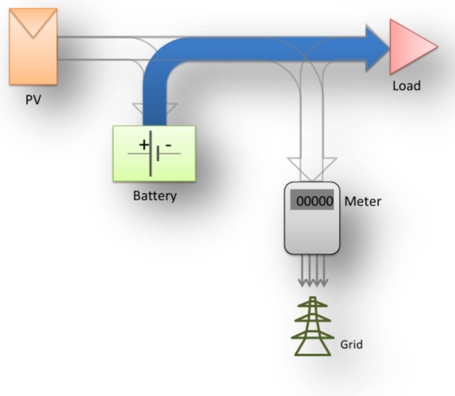


Figure 35: Energy flow discharge

Based on the ratio of demand to generation and the storage capacity the actual energy flow has to be controlled using the relevant energy flow scenario. This scheduling is done by an energy management system which might control not only the energy production and energy storage system but also the actual load.

5.3.2.1 Energy Flow Scheduling

The scheduling algorithm is rather simple – if the storage state of charge is above the lower limit the first check is if the rating is sufficient for the required power, otherwise the actual charge/discharge will be adjusted.

```
charge = generation - load

If (rating > 0) And (Abs(charge) / TIME_SPAN > rating) Then

    charge = Sgn(charge) * rating * TIME_SPAN

    If (charge > 0) Then

        surplus = generation - (load + charge)

    Else

        demand = load - (generation - charge)

    End If

End If
```

The two cases are considered – when the available generation is larger than the required load, the storage system can be charged, but only to the maximum state of charge allowed. The remaining energy is then considered to be surplus and can be fed to the grid. If the load is larger than the generation the energy storage system is discharged but only to the minimum state of charge specified.

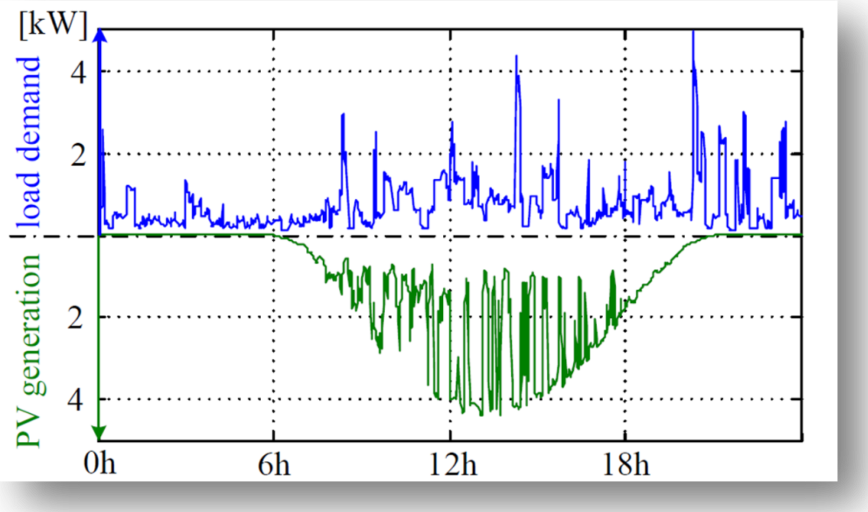
```
If (generation > load) Then

    If (soc_old < soc_max) Then

        If charge > (soc_max - soc_old) * capacity Then

            charge = (soc_max - soc_old) * capacity
            surplus = generation - (load + charge)

        End If

    Else

        charge = 0
        surplus = generation - load

    End If

Else

    If (soc_old > soc_min) Then

        If charge < (soc_min - soc_old) * capacity Then

            charge = (soc_min - soc_old) * capacity
            demand = load - (generation - charge)

        End If

    Else

        charge = 0
        demand = load - generation

    End If

End If
```

Any energy still required to cover the load demand is calculated as additional demand drawn from the grid as depicted in the energy flow scenarios above.

Since the basic input parameters are useful even in case of different storage technologies also other EESS can be modeled. However, some storage specific issues have to be taken into account when they are compared. Since no exact model of the storage system is used other parameters influencing the storage capacity such as number of deep discharge cycles have to be considered. Depending on the battery design and specification the SOC limits can be used to cover some of the limitations of the simplified model.

5.3.3 PV Intermittency

One of the major issues with typical PV generation values is that they are commonly just average values for a particular location.



Source: (Martin Braun, 2009)

Figure 36: Daily fluctuations - demand and generation

When the daily generation for a PV plant is calculated the global irradiation at the chosen location is used. Those values usually are between the diffuse irradiation (minimum) and the clear sky irradiation (maximum) as shown in the next figure:

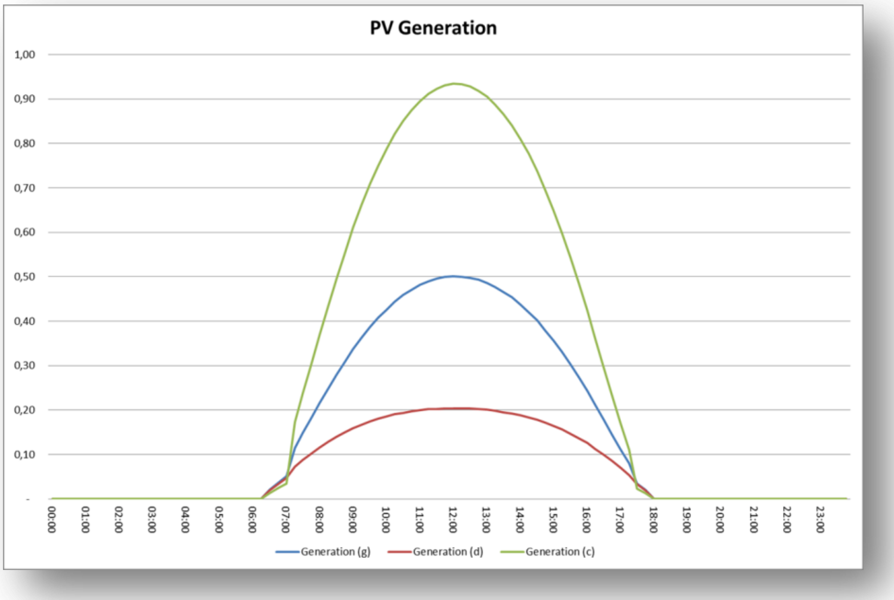


Figure 37: Diffuse, global and clear sky irradiation

The actual variation of the irradiation data at a location is therefore varying between the minimum value and the maximum at a particular time interval. Moving clouds are usually the main reason for the varying output.

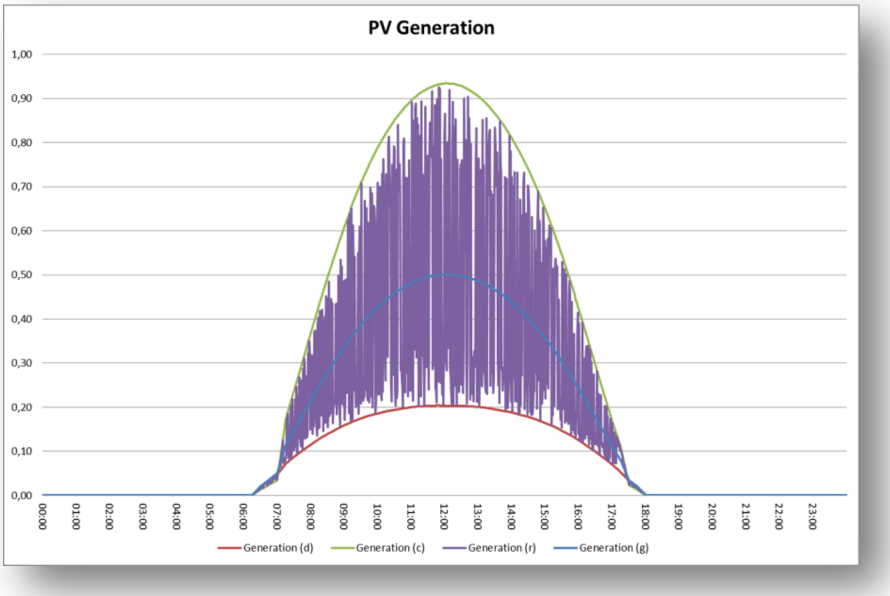


Figure 38: Random variation of PV generation

However, the average value is the global irradiation value. So for the simulation within a particular 15 min interval it is rather easy to correct the calculation for peaks in the PV production.

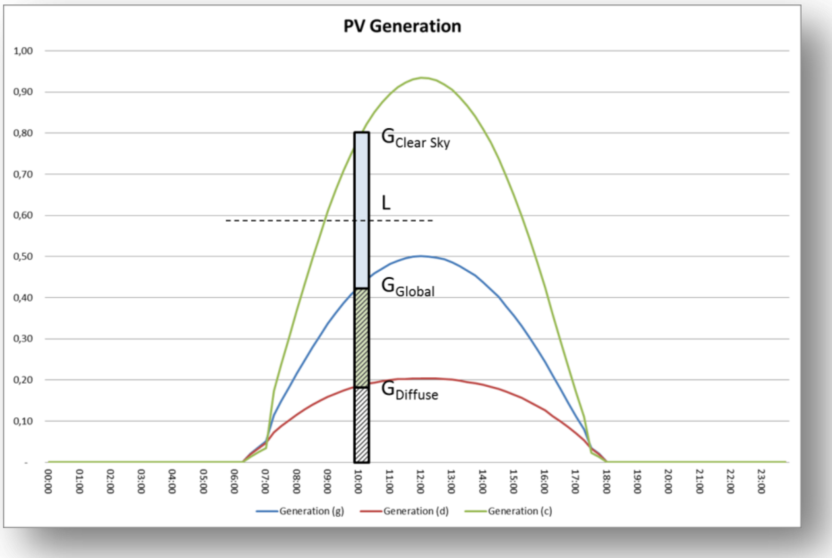


Figure 39: Calculation parameter at a time interval

If no random variations occur, the actual parameters for load (L) and the generation based on the value of global irradiation (G_{Global}) determine the energy flow in the simulation at a particular (15 min) time interval.

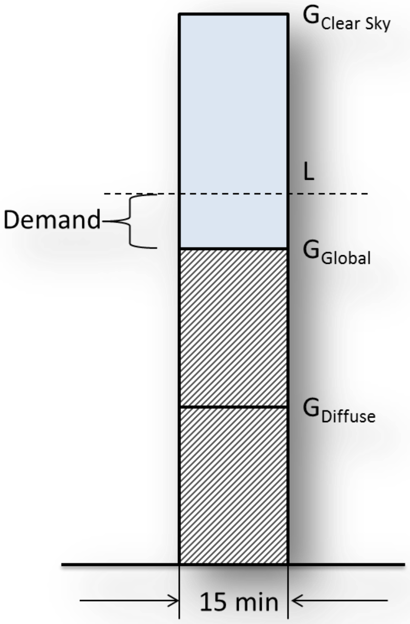


Figure 40: Basic surplus / demand calculation

If the sky would be always covered with clouds the global irradiation generation should be more close to the diffuse irradiation value. Also for a clear sky the global irradiation would match the clear sky value. If the global variation is in between, the calculation can simply assume that only a part of the time interval has clear sky irradiation, the other remaining part would be closer to the diffuse irradiation value.

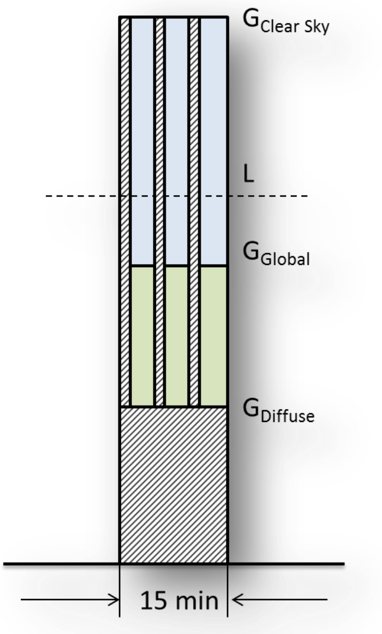


Figure 41: Variation in PV production (intermittency)

Since the available generation values based on clear sky irradiation, global irradiation, and diffuse irradiation are known, the generation has a maximum deviation (from diffuse to clear sky) and a certain distribution of those deviations. The area of the PV production is the same as in the basic calculation (based on the global irradiation). The combination of the PV output is based just on the average global irradiation.

$$G_{Global} * t_{Interval} = G_{Clear\ Sky} * \Delta t + G_{Diffuse} * (t_{Interval} - \Delta t)$$

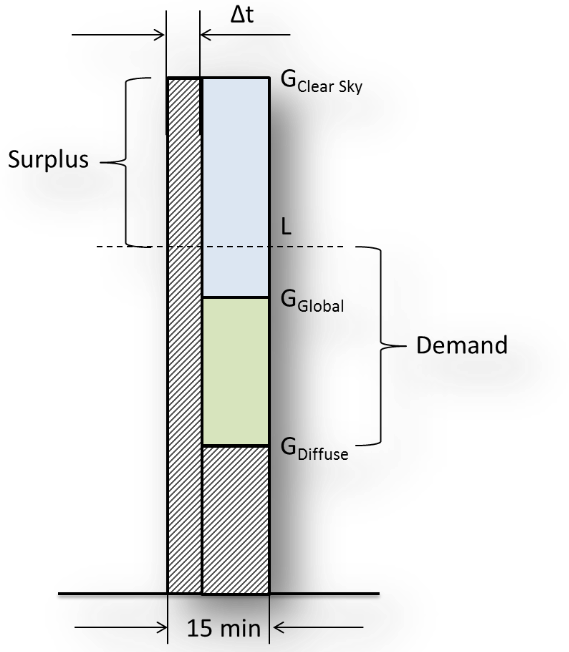
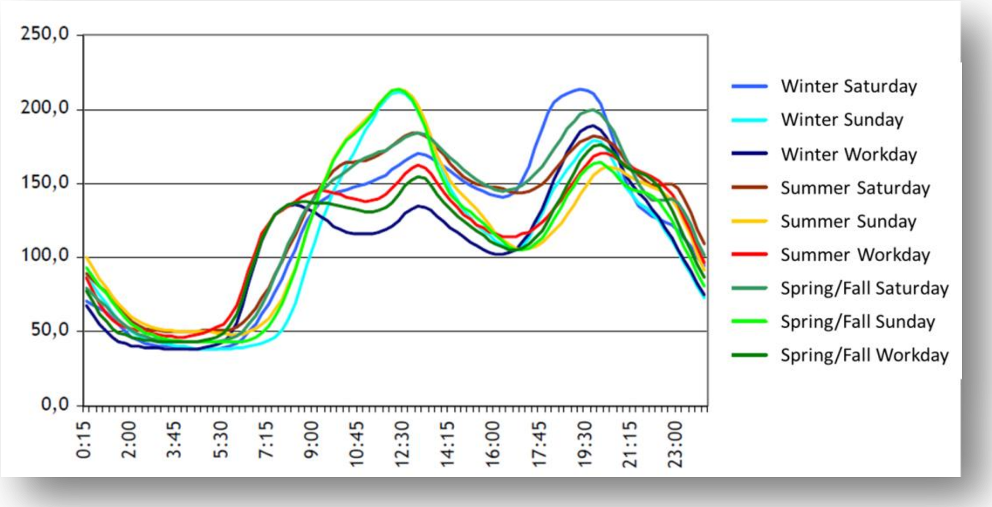


Figure 42: Corrected surplus / demand calculation

Since the clear sky generation can be larger than the actual required load, the overall demand increases. The simulation can correct using the depicted values to correct for the PV generation intermittency.

5.3.4 Load Data

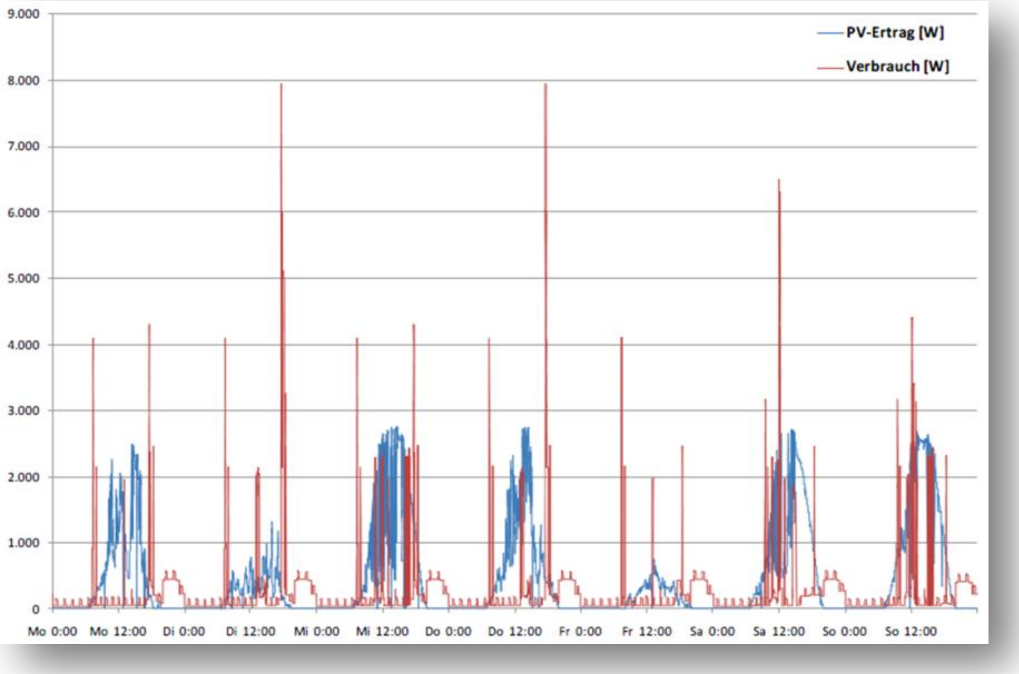
Similarly, load data are often based on available standard load profiles (SLP).



Source: (Ing. Otto Kalab, Wirtschaftskammer OÖ, 2011)

Figure 43: Standardized Load Profiles (households)

The actual use at a single location (e.g. household) can show high peaks in the load profile.



Source: (Mark Bost, 2011)

Figure 44: Daily load peaks

If a scenario with several households is modeled, the average load profile is sufficient – for single households the case of localized high load peaks have to be considered.

The actual load data have to be monitored in detail (actual measurements) to get meaningful data. And even in this case the variability of the personal behavior is rather large and difficult to model. For the simulation a correction can be made by simply assuming that high peaks can occur daily and those load values cannot simply be provided by the PV generation. Therefore, the average load during the day is reduced, but the demand is increased.

5.4 Data

5.4.1 PV Generation data

In order to drive the simulation with reasonable values datasets for the PV production and the load have to be provided. If the PV production data are based on real measurements they can simply be used. The data (365 days times 96 daily 15 min intervals) have to be available. In order to allow for a wide variation of location scenarios, the PV generation data from the PVGIS website (PVGIS, 2011) have been integrated by additional Microsoft Excel worksheets.

The Photovoltaic Geographical Information System (PVGIS) is freely available and can be used for a wide variety of locations.

Source: (PVGIS, 2011)

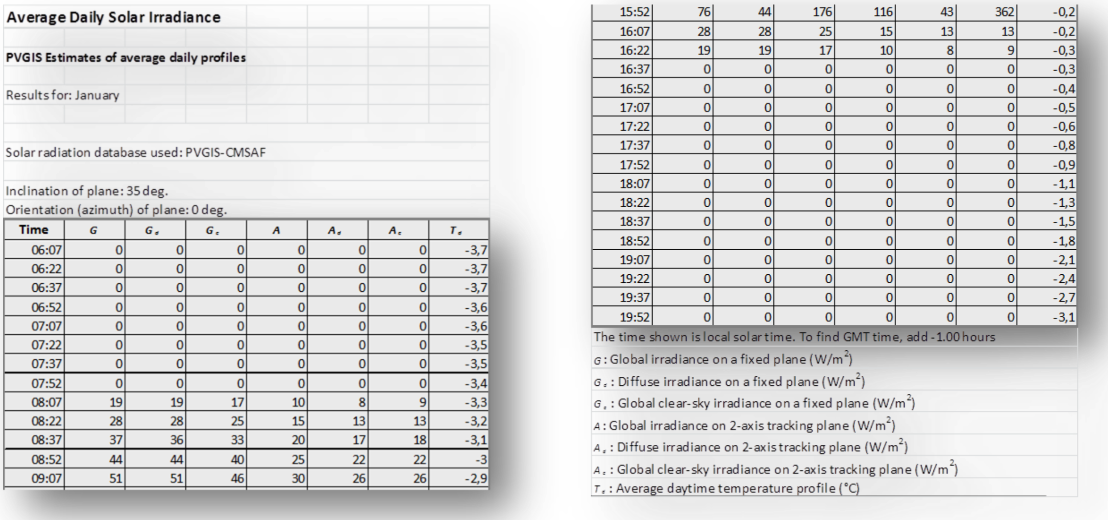
Figure 45: PVGIS Europe

The detailed information on the data available can be retrieved from the PVGIS website.

> *Solar energy is one of the environmentally sustainable resources for producing electricity using photovoltaic (PV) systems. The main input data used in the planning process is solar radiation. We have developed a solar radiation database from climatologic data homogenized for Europe and available in the European Solar Radiation Atlas…*

> *…The model algorithm estimates beam, diffuse and reflected components of the clear-sky and real-sky global irradiance/irradiation on horizontal or inclined surfaces. The total daily irradiation [Wh.m^{-2}] is computed by the integration of the irradiance values [W.m^{-2}] calculated at regular time intervals over the day. For each time step during the day the computation accounts for sky obstruction (shadowing) by local terrain features (hills or mountains), calculated from the digital elevation model.*

The main data input is based on those output reports from the interactive charts available.



Average Daily Solar Irradiance

PVGIS Estimates of average daily profiles

Results for: January

Solar radiation database used: PVGIS-CMSAF

Inclination of plane: 35 deg.
Orientation (azimuth) of plane: 0 deg.

Time	G	G_d	G_c	A	A_d	A_c	T_d
06:07	0	0	0	0	0	0	-3,7
06:22	0	0	0	0	0	0	-3,7
06:37	0	0	0	0	0	0	-3,7
06:52	0	0	0	0	0	0	-3,6
07:07	0	0	0	0	0	0	-3,6
07:22	0	0	0	0	0	0	-3,5
07:37	0	0	0	0	0	0	-3,5
07:52	0	0	0	0	0	0	-3,4
08:07	19	19	17	10	8	9	-3,3
08:22	28	28	25	15	13	13	-3,2
08:37	37	36	33	20	17	18	-3,1
08:52	44	44	40	25	22	22	-3
09:07	51	51	46	30	26	26	-2,9

15:52	76	44	176	116	43	362	-0,2
16:07	28	28	25	15	13	13	-0,2
16:22	19	19	17	10	8	9	-0,3
16:37	0	0	0	0	0	0	-0,3
16:52	0	0	0	0	0	0	-0,4
17:07	0	0	0	0	0	0	-0,5
17:22	0	0	0	0	0	0	-0,6
17:37	0	0	0	0	0	0	-0,8
17:52	0	0	0	0	0	0	-0,9
18:07	0	0	0	0	0	0	-1,1
18:22	0	0	0	0	0	0	-1,3
18:37	0	0	0	0	0	0	-1,5
18:52	0	0	0	0	0	0	-1,8
19:07	0	0	0	0	0	0	-2,1
19:22	0	0	0	0	0	0	-2,4
19:37	0	0	0	0	0	0	-2,7
19:52	0	0	0	0	0	0	-3,1

The time shown is local solar time. To find GMT time, add -1.00 hours
G : Global irradiance on a fixed plane (W/m^2)
G_d : Diffuse irradiance on a fixed plane (W/m^2)
G_c : Global clear-sky irradiance on a fixed plane (W/m^2)
A : Global irradiance on 2-axis tracking plane (W/m^2)
A_d : Diffuse irradiance on 2-axis tracking plane (W/m^2)
A_c : Global clear-sky irradiance on 2-axis tracking plane (W/m^2)
T_d : Average daytime temperature profile (°C)

Source: (PVGIS, 2011)

Figure 46: PVGIS - Daily Report

The data used to create the PV generation data are:

- G: Global irradiance on a fixed inclined plane (W/m^2)
- G_d: Diffuse irradiance on a fixed inclined plane (W/m^2)
- G_c: Global clear-sky irradiance on a fixed inclined plane (W/m^2)
- T_d: Average daytime temperature profile (°C)

Note that the PVGIS information systems also could provide the irradiation values for an inclined axis tracking system or for a 2-axis tracking system.

5.4.2 PV Power Model

Since no generation data for the complete PV plant are calculated in the daily report, the actual power output is calculated according to a model presented in the accompanying literature (Huld T., 2009).

The power output depends only on the module temperature T_{mod} and the actual irradiance G on the fixed inclined plane:

$$P(G, T_{mod}) = P_{STC} \cdot \frac{G}{G_{STC}} \eta_{rel}(G', T')$$

P_{STC} is the power at standard test conditions (STC) of $G_{STC} = 1000\ W/m^2$ and $T_{mod} = 25°C$.

The relative efficiency η_{rel} is given by:

$$\eta_{rel} = 1 + k_1 \ln(G') + k_2[\ln(G')]^2 + T'(k_3 + k_4 \ln(G') + k_5[\ln(G')]^2 + k_6 T')$$

And G' and T' are normalized parameters to STC values.

$G' \equiv G/G_{STC}$ and $T' \equiv T_{mod} - T_{STC}$

The coefficients k_1 to k_6 used are:

Coefficient	c-Si	CIGS	CdTe
k1	-0.017162	-0.005521	-0.103251
k2	-0.040289	-0.038492	-0.040446
k3	-0.004681	-0.003701	-0.001667
k4	$1.48 \cdot 10^{-4}$	$-8.99 \cdot 10^{-4}$	-0.002075
k5	$1.69 \cdot 10^{-4}$	-0.001248	-0.001445
k6	$5 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$-2.3 \cdot 10^{-5}$

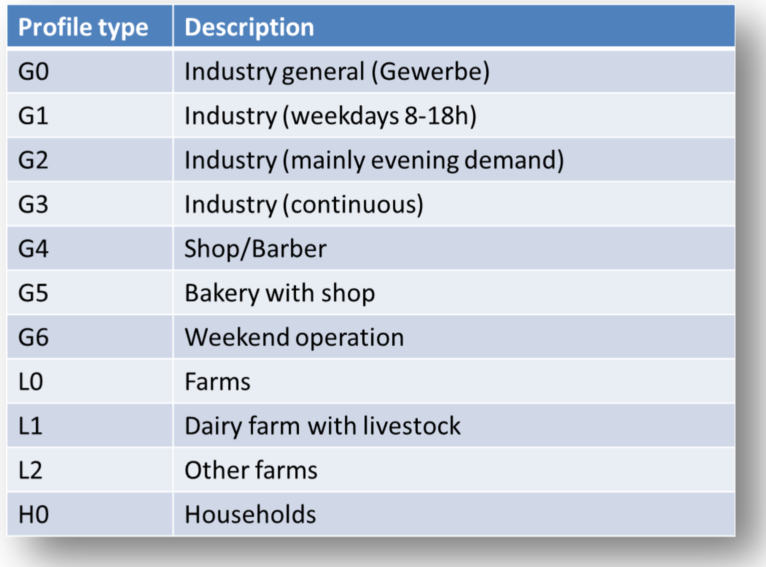
Source: (PVGIS, 2011), (Huld T., 2009).

Table 3: Model Coefficients

The actual data used in the calculation are for *c-Si* (crystalline Silicon).

5.4.3 Load Profile data

The load profile data are based on the VDEW standardized load profiles available from several websites (Verfahren zur Berechnung der Lastprofile bei Kleinkunden, 2011). Those profiles usually contain datasets for different types of consumers.



Profile type	Description
G0	Industry general (Gewerbe)
G1	Industry (weekdays 8-18h)
G2	Industry (mainly evening demand)
G3	Industry (continuous)
G4	Shop/Barber
G5	Bakery with shop
G6	Weekend operation
L0	Farms
L1	Dairy farm with livestock
L2	Other farms
H0	Households

Source: Standardlastprofil - Wikipedia (Standardlastprofil, 2011)

Table 4: SLP types

The load profiles are used by the distribution system operator for the load demand forecast. A standardized load profile (SLP) is normalized for 1000 kWh annual consumption. In the simulation calculation the actual load is determined by multiplying the load profile date (every 15 min on every day of the year) with the load factor (e.g. 4.5 to yield a total yearly consumption of 4500 kWh).

Besides the PV generation data and the load profile (every 15 min for every day of the year) the storage parameters as described above are needed to apply the energy management scheduling algorithm. The results calculated are the storage state (capacity) of the energy storage system (state of charge – SOC), the surplus fed into the grid, and the additional demand from the grid. Those data (again available for every 15 min interval for every day of the year) can be plotted to present the simulation results for further analysis. Additional charts (daily distribution for generation, load, charge, surplus, demand, and SOC) can be easily generated.

5.5 Results

The simulation tool uses the basic PVGIS input data and the ENWG based load profile data to drive the actual simulation calculation. Several outputs can be retrieved:

- PV Generation
- Load Profile
- Charge / Discharge
- Surplus
- Demand
- Stored Energy
- State of Charge (SOC)

5.5.1 PV Generation

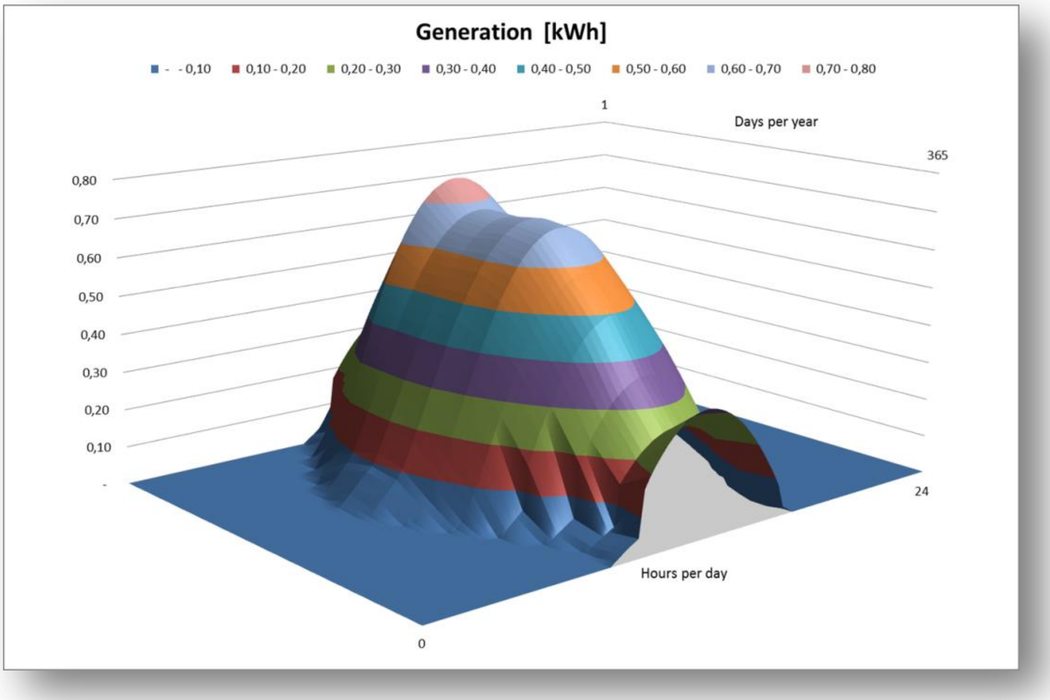


Figure 47: PV Generation

All data presented her are input data into the actual calculation. Since the PVGIS irradiation data are available for 15 minute intervals on a typical day in every month (96 data points, 12 times for a year) the data have to be interpolated to get values for every day of the year (365 days). The resulting irradiation data set (35040 data points) is used to calculate the PV generation. The power output is scaled with the PV factor (kWp) and plotted over the hours per day and the day per year.

It is interesting to note that for the data sample shown here, the maximum generation is not during the summer but in the spring, due to lower temperature and better climatic conditions.

5.5.2 Load Profile

The load data are available directly without any modifications. Since they are normalized the load factor (e.g. 4.5 for a typical 4 person household) is applied to yield the actual load for every 15 min interval.

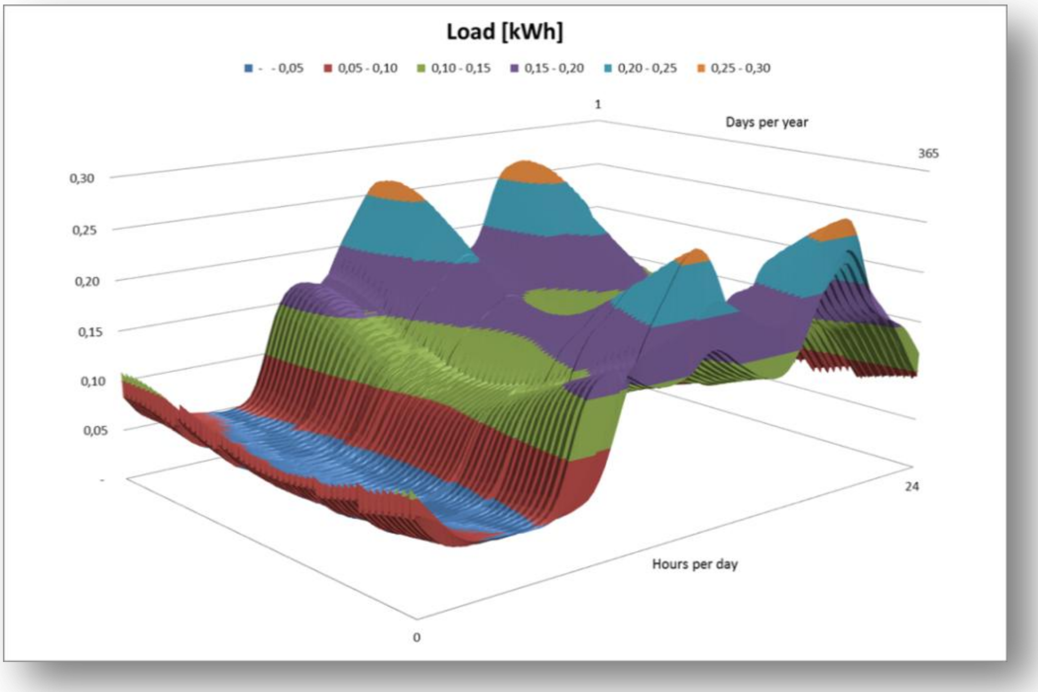


Figure 48: Load Profile H0 Households

Note that the difference in the load profile during the week and on weekends leads to a shift of the daily load curve. For the standardized load profile used here (H0

Households) the minimum load occurs during night (first hours of the day) and the peak consumption can be found around noon and in the evening.

The load profile plot also reveals that the load requirements during the winter are higher than during the summer months. Note that the standardized load profile data (1000 kWh per year total) are scaled by the load factor to yield the actual load requirements (e.g. 4500 kWh).

5.5.3 Charge / Discharge

The charge / discharge plot show that the battery capacity used in this example cannot provide enough energy during the winter months to provide enough energy.

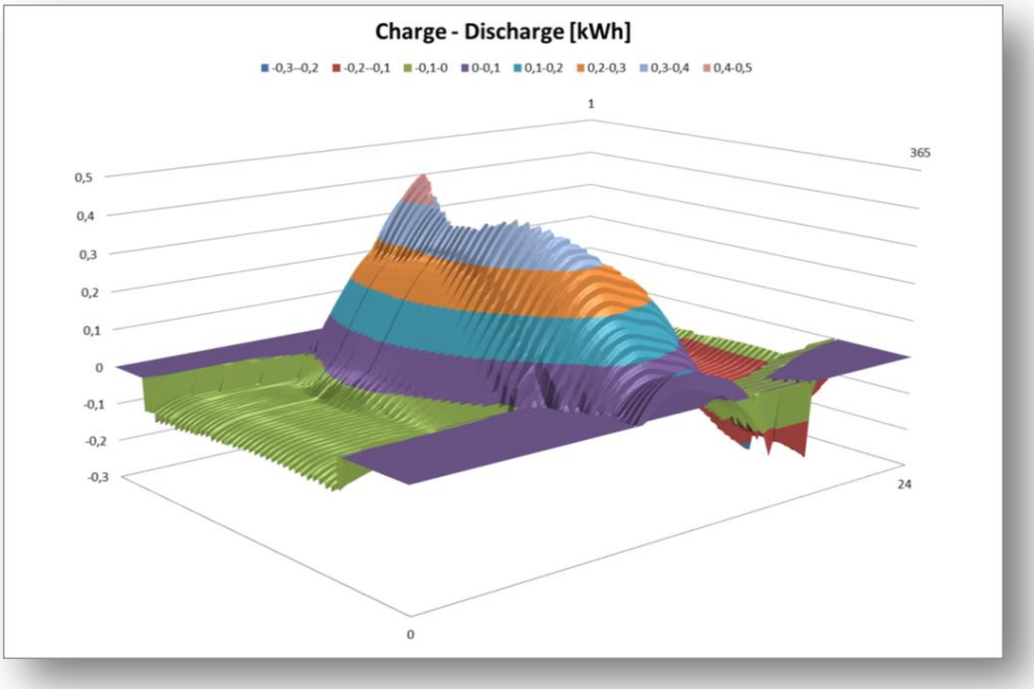


Figure 49: Battery Charge / Discharge

Since the charging / discharging strategy is to limit the state of charge (SOC) values of the battery within predefined limits (e.g. 20% minimum SOC, and 80% maximum) the capacity of the battery determines the actual charge and discharge.

During winter the example shown here indicates that the battery is fully discharged in the evening and cannot be charged adequately during the day. On a typical day during the summer the battery is not completely discharged and is charged to the maximum during the day, thus providing the necessary energy to fulfill the load requirements.

5.5.4 Surplus

The PV generation drives the charging process – however, since there is a limit in the total capacity of the electrical storage system not all energy can be stored and is therefore transferred to the grid as a generation surplus.

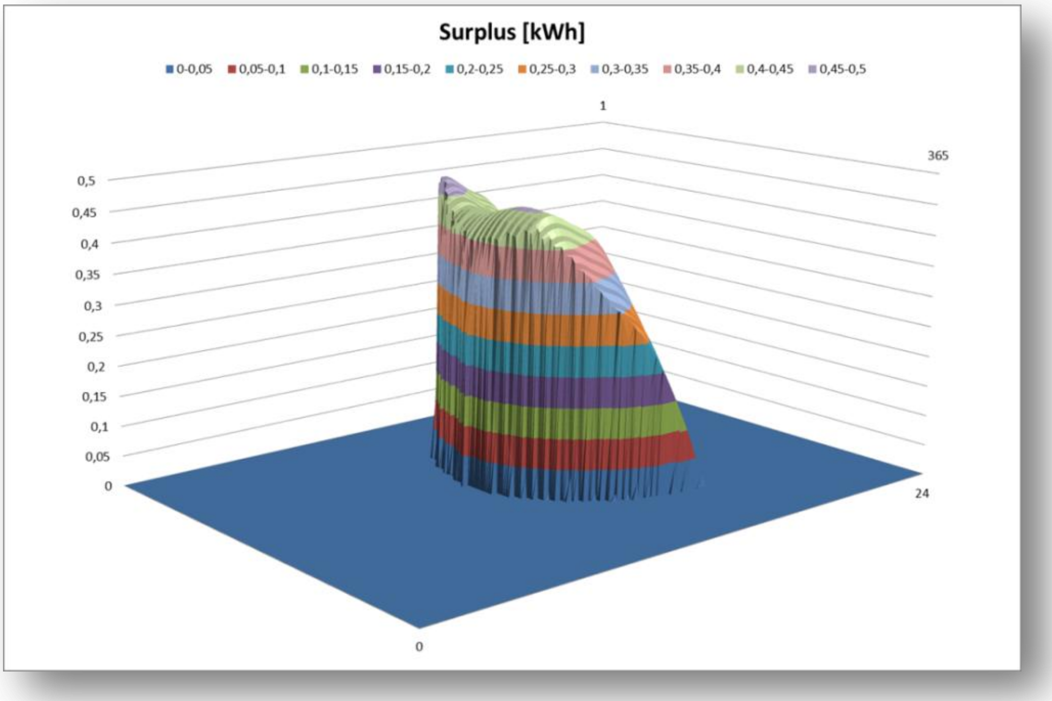


Figure 50: Surplus

The surplus, which occurs during the summer months, is fed back into the grid, since it cannot be used locally. It is clear that if the capacity of the battery is increased, the amount of surplus will decrease.

5.5.5 Demand

The configuration used in the example shows that during the winter months not all needed electric energy can be provided only by PV generation and the electric energy storage system. The grid has to supply the missing energy (energy necessary to cover the load demand, which cannot be supplied locally) to fulfill the demand.

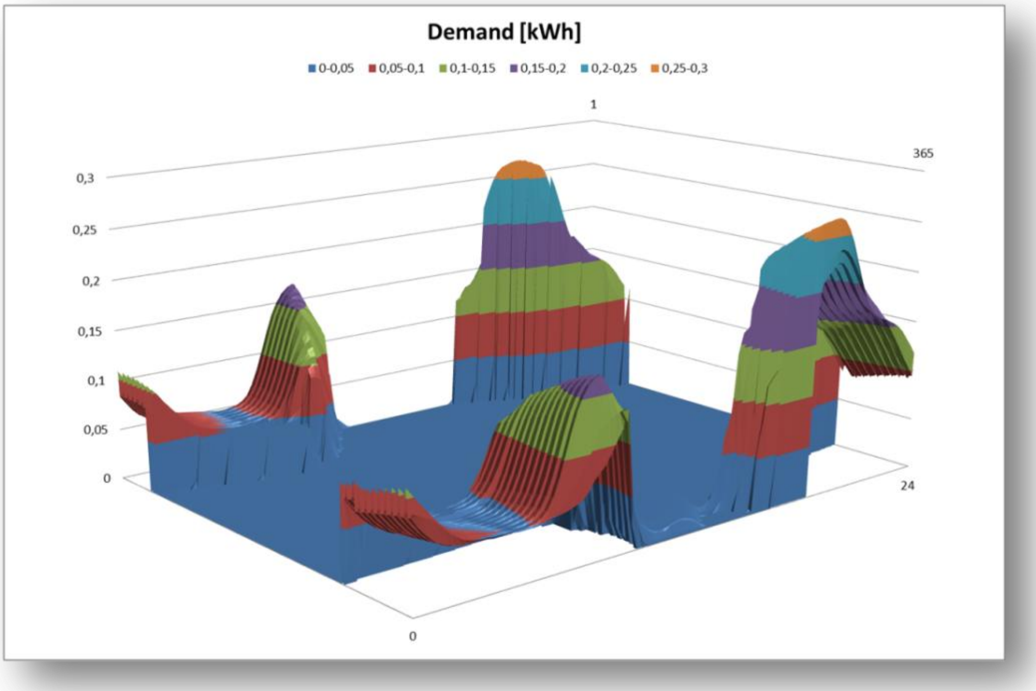


Figure 51: Demand Profile

Note that typically the demand is still high during the winter months (when no PV production is available and the battery is drained). Also for the selected scenario, the midday peak load can almost be covered throughout the year, but the evening peak cannot be supplied, so other sources of electricity have to be employed.

5.5.6 Stored Energy

The energy storage system operates within predefined limits (SOC_{min}. SOC_{max}). If the state of charge drops below the lower limit, no further discharge is scheduled, if the state of charge reaches the upper limit, no further charging is allowed.

Since the useful range of SOC depends on the selected battery technology, the values can be changed to check the impact of different technologies. However, the limitation of the SOC range simply means that the actual storage capacity is simply somewhat lower (e.g. for the selected limits of 20% and 80% the capacity is just 60%).

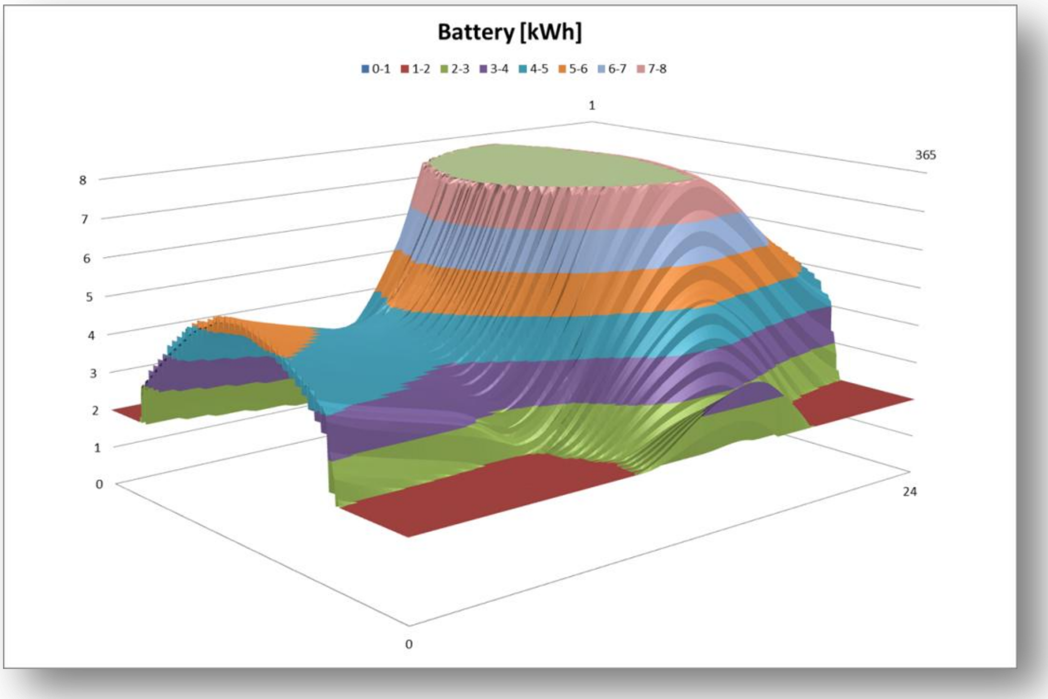


Figure 52: Energy stored in battery

The energy stored in the battery is plotted again over the hours of the day and the day of the year. This is the main result of the calculation since it shows the actual usage of the electrical energy storage system.

Note that for the State of Charge (SOC) the result is similar to the plot shown. Simply the scale is normalized between 0% and 100%.

5.5.7 Daily Profiles

The result set (35040 data points) can be easily analyzed for every day of the year. The typical daily profiles are:

- generation
- load
- charge/discharge
- surplus
- demand
- SOC

The examples shown here are for the 1st of March 2011.

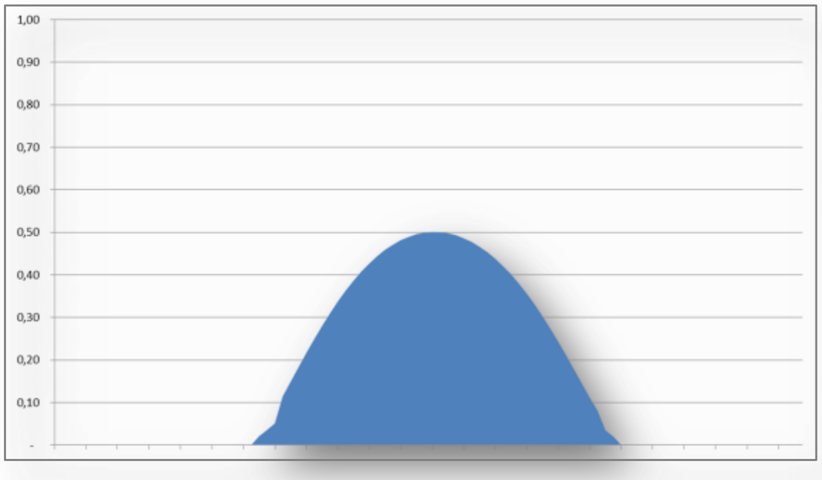


Figure 53: Daily Data – Generation

The daily PV generation profile is based on the global irradiation data. Note that in the morning the lower values indicate diffuse irradiation and the jump to the global irradiation data is due to shading based on the horizon (mountains). A similar, but less prone effect can be seen in the evening. The actual PV production does not only depend on the climatic conditions but of course on the specific geographical surroundings. Note that additional shading due to houses, trees etc. is not included.

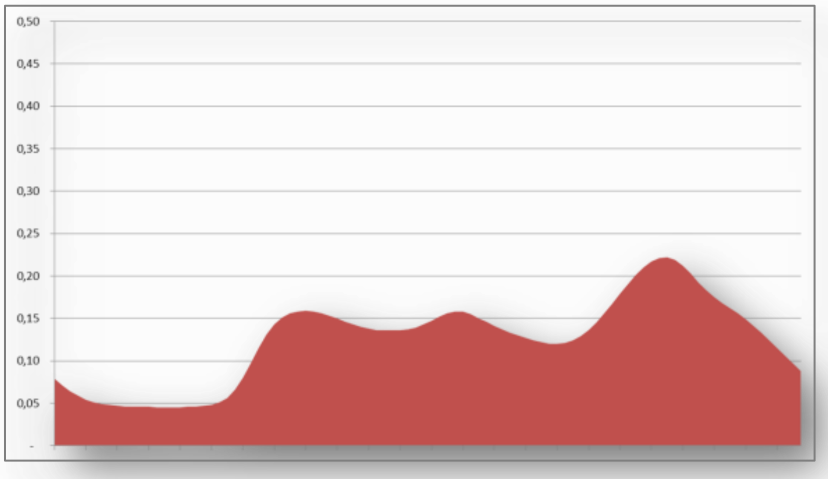


Figure 54: Daily Data – Load

The daily load curve is based on the standardized load profile for single households and shows the typical load consumption peeks.

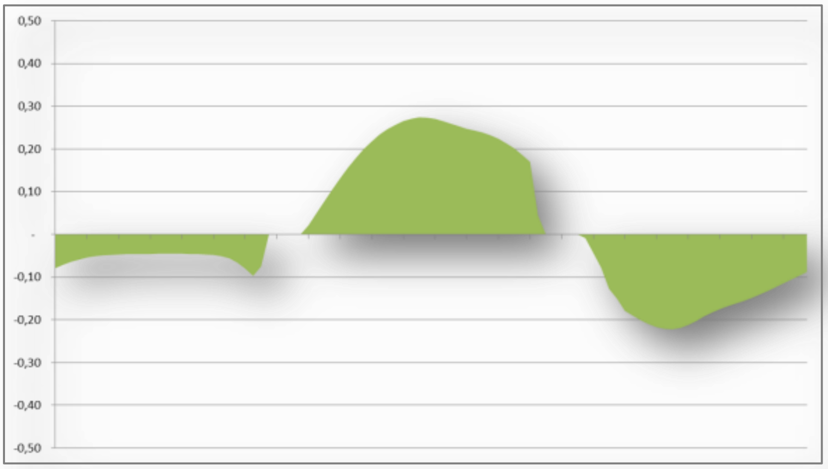


Figure 55: Daily Data - Charge/Discharge

The resulting charge / discharge profile on theis particular day shows that the battery is discharged during the night and well into the morning, charged during the day, and again discharged during the evening. The two sections where no charging or discharging occurs is due to the limits of the battery capcity as shown below.

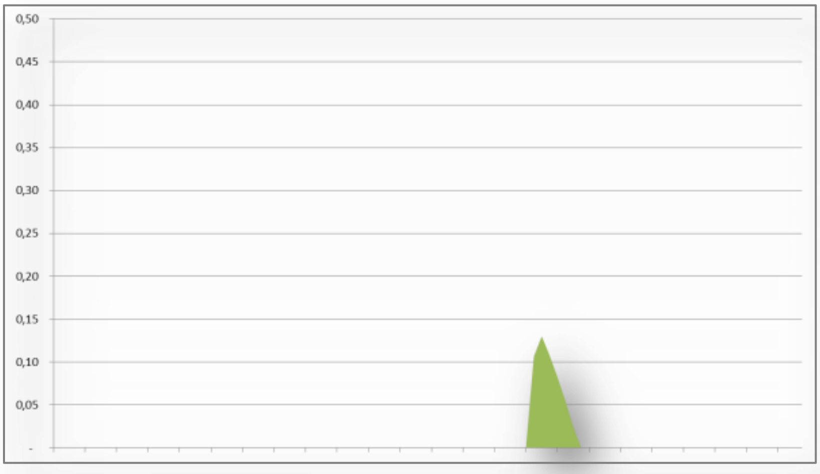


Figure 56: Daily Data – Surplus

The plot of the daily surplus profile shows that in the afternoon the battery is fully loaded and the additionally PV generated electricity cannot be used locally. Therefore this amount is fed back into the grid.

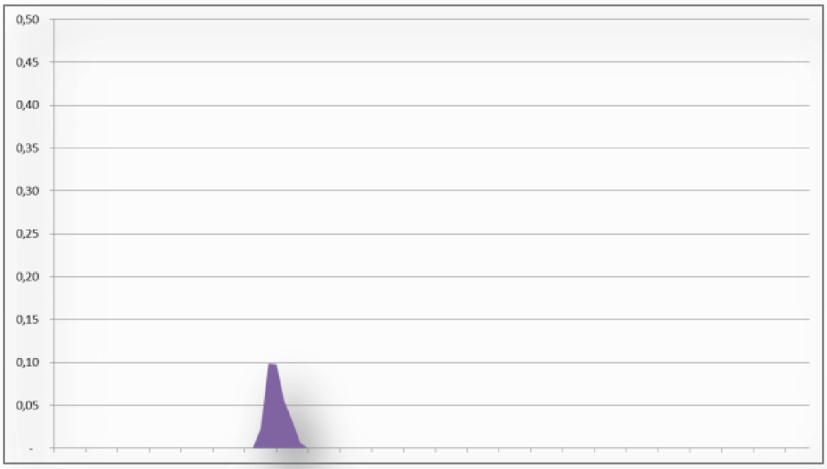


Figure 57: Daily Data – Demand

In the morning, when the load is still high, the battery has been drained to the specified minimum, and the required electricity has to be supplied by the grid leading to a short peak in the daily demand profile.

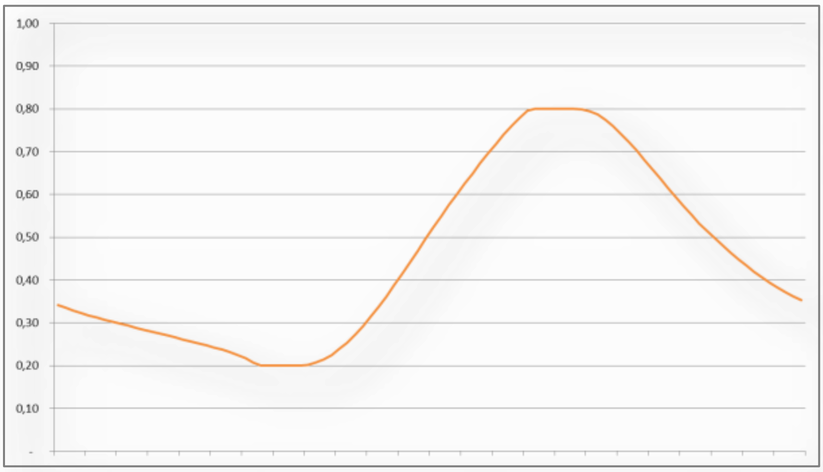


Figure 58: Daily Data – SOC

The SOC plot for this day shows the limitation of the storage capacity – in the morning the lower SOC limit has been reached, and during the afternoon the maximum SOC value limits the charging action. Every time the $SOC_{minimum}$ is reached, any load has to be supplied by the grid, ever time the $SOC_{maximum}$ is reached and available PV generation has to be fed to the grid.

5.5.8 Comparison Battery vs. No Battery

It is also interesting to compare the simulation for a particular day with no electric energy storage system.

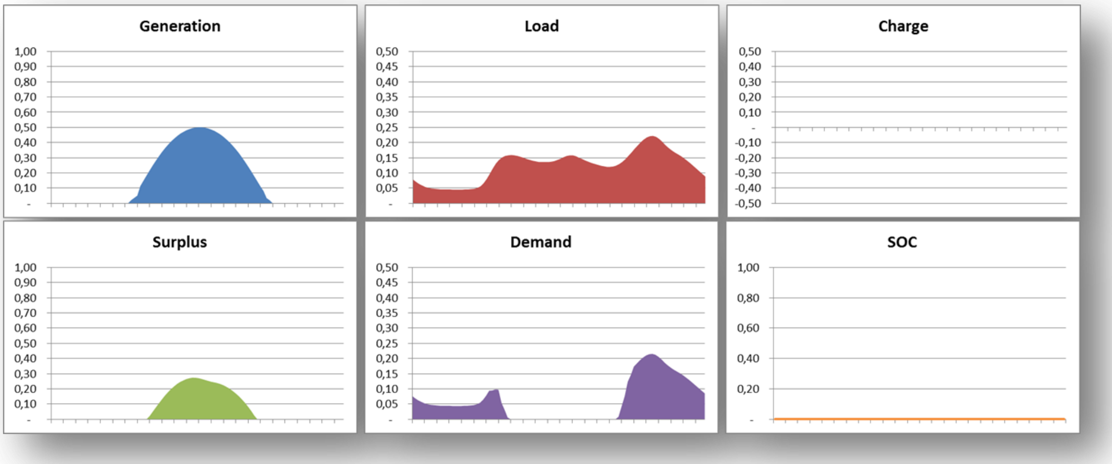


Figure 59: 1st March - all values in kWh, SOC 0-1 (no battery)

The simulation for the day without an electric energy storage system shows the total surplus and demand profile, where the amounts fed into grid and supplied by the grid are considerable higher.

5.5.9 Battery 10 kWh

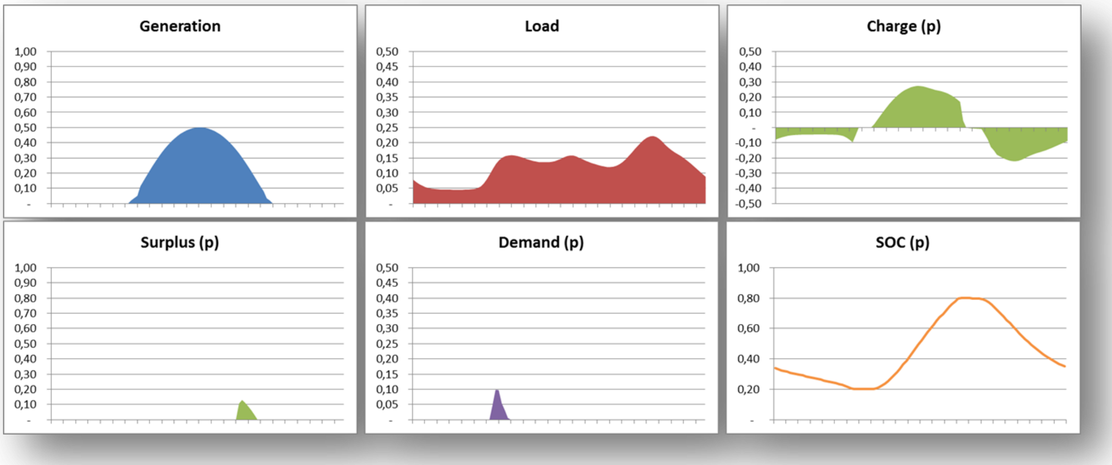


Figure 60: 1st March - all values in kWh, SOC 0-1 (10 kWh battery)

The figures above are the same as presented before just for comparison.

The data can also be shown for the monthly averages:

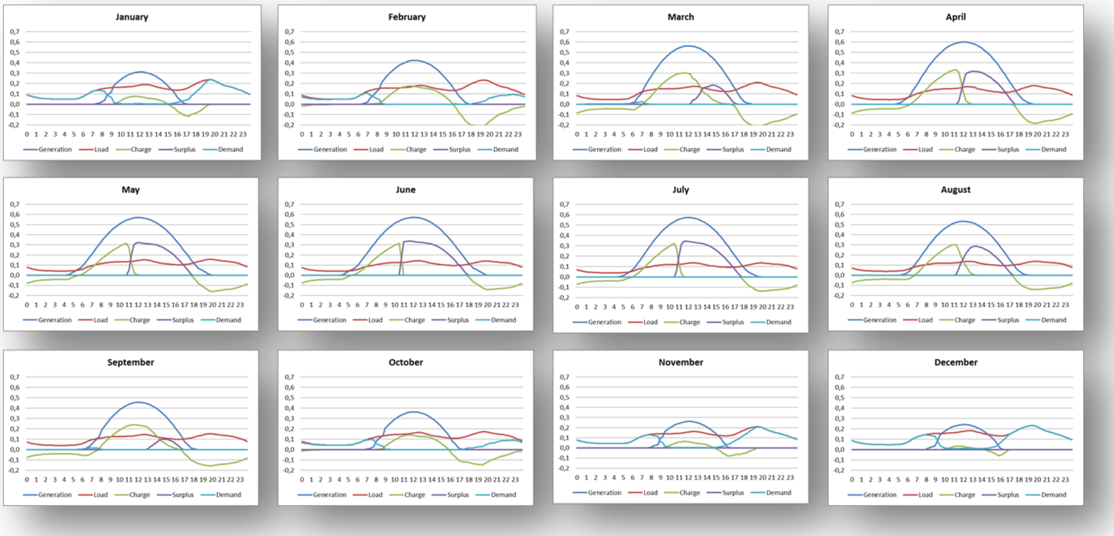


Figure 61: Simulation results (monthly average)

For more samples see the appendix chapter 8.2.

The results show good correlation to results in other tools and studies. They generated PV power is consistent with the average yearly results from the PVGIS website. The simulation results for the presented scenario correspond with results from the literature. If the local load peaks are taken into account (or a custom load profile is used) the utilization of the PV generation and the surplus / demand calculation is in line with the literature results.

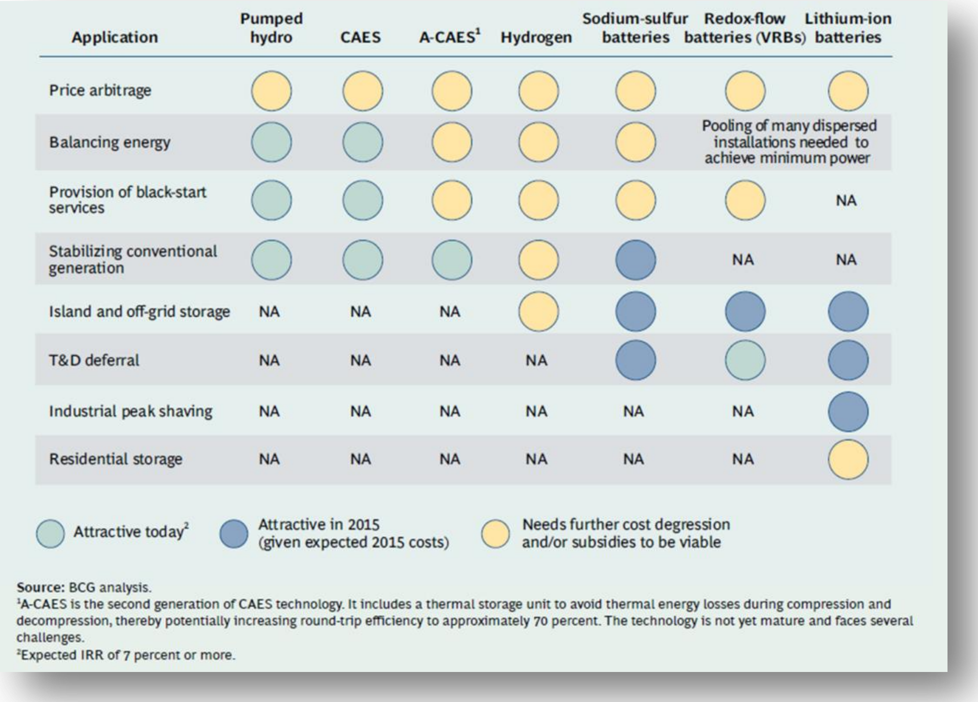
5.6 Business Case

In a recent study (Cornelius Pieper and Holger Rubel, 2011) a business case analysis for eight storage applications combined with different storage technologies shows that good financial returns are possible – especially for energy balancing, generation stabilization, and off-grid electricity storage. This is even possible with no subsidies or other additional sources of revenue by assuming 2015-2020 costs.

They state that

> *As the use of renewable energy and technologies mature, the market for storage will gradually increase, reaching approximately €10 billion annually by 2020 and offering string first-mover advantages to a range of potential stakeholders.*

The growing demand for storage presents a wide range of business opportunities for energy companies, utilities, and related players alike. Especially smaller utilities are more likely to be flexible and open to explore the new prospects. Since the required investments are considerable, many small independent power producers (IPPs) will likely form alliances to implement larger storage projects.



Application	Pumped hydro	CAES	A-CAES[1]	Hydrogen	Sodium-sulfur batteries	Redox-flow batteries (VRBs)	Lithium-ion batteries
Price arbitrage	🟡	🟡	🟡	🟡	🟡	🟡	🟡
Balancing energy	🟢	🟢	🟡	🟡	🟡	Pooling of many dispersed installations needed to achieve minimum power	
Provision of black-start services	🟢	🟢	🟡	🟡	🟡	🟡	NA
Stabilizing conventional generation	🟢	🟢	🟢	🟡	🔵	NA	NA
Island and off-grid storage	NA	NA	NA	🟡	🔵	🔵	🔵
T&D deferral	NA	NA	NA	NA	🔵	🟢	🔵
Industrial peak shaving	NA	NA	NA	NA	NA	NA	🔵
Residential storage	NA	NA	NA	NA	NA	NA	🟡

🟢 Attractive today[2]
🔵 Attractive in 2015 (given expected 2015 costs)
🟡 Needs further cost degression and/or subsidies to be viable

Source: BCG analysis.
[1] A-CAES is the second generation of CAES technology. It includes a thermal storage unit to avoid thermal energy losses during compression and decompression, thereby potentially increasing round-trip efficiency to approximately 70 percent. The technology is not yet mature and faces several challenges.
[2] Expected IRR of 7 percent or more.

Source: (Cornelius Pieper and Holger Rubel, 2011)

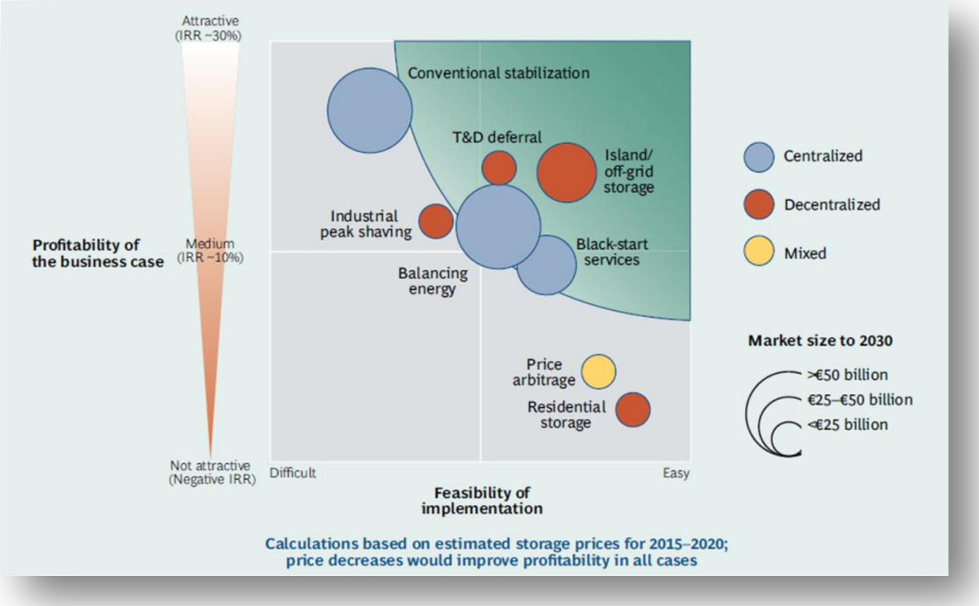
Figure 62: Financial Attractiveness of Electricity Storage Applications

The island and off-grid storage scenario seems to be already attractive in the near future, where the residential storage scenario discussed so far needs further cost degression.

The expected decrease in storage costs and the expected increase in energy costs will further drive the adoption of storage. The added incentive like the self-consumption bonus for PV generation of approximately €0.08 per kWh in Germany cannot offset the required investment costs.

However, the push to a higher degree of energy independence for municipals and regions – energy self-sufficient regions (Bruno Abegg, 2010) will play into the feasibility of energy storage supported photovoltaic power plants.

Also the combined size of several household sized domestic photovoltaic power generation to a larger virtual power generation system for a municipal or region could allow the implementation of larger projects which could be feasible due to the economy of scale.



Calculations based on estimated storage prices for 2015–2020; price decreases would improve profitability in all cases

Source: (Cornelius Pieper and Holger Rubel, 2011)

Figure 63: Attractiveness of Storage Business Cases in the Near Future

In the long run even residential storage systems will be attractive because of the relative ease of implementation. The similarity to the island/off-grid storage scenarios is even more pronounced assuming that autarky is an important benefit of such scenarios.

Technology	€/kWh	$/kWh	€/kW	$/kW
Pb-Acid	50 – 270	50 – 400	140 – 200	175 – 600
NiCd		400 – 2400		175 – 1500
Li-ion	500 – 2000	500 – 2500		175 – 4000
NaS	210 – 250	250 – 500	125 – 150	150 – 3000
NaNiCl	600	100 – 800		150 – 300
Va Redox	125 – 150	150 – 1000		175 – 5000
ZnBr		500 – 1000		175 – 2500
Supercaps		300 – 5000	70 – 400	100 – 350
Flywheel		300 – 5000	140 – 350	250 - 350

Source: (Bella Espinar, 2011)

Table 5: Energy and power cost for energy storage technologies

6 Conclusions

The result of the simulation show that the simple calculation can be used to gather more detailed understanding about typical scenarios for storage supported renewable energy generation. The use of an electric energy storage system extends the local use of locally generated renewable energy. Since the actual demand of grid supplied energy is reduced considerably the implementation of grid connected (even hybrid) eases the load on the grid. In many areas where the grid stability is problematic or the additional PV generated energy cannot be easily accommodated for, the use of a local electric storage system allows the extensive utilization of renewable energy. Since the additional costs of storage can only be offset by the cost of electricity supplied by the grid saved the electric storage systems will currently be only economical if either the energy production is expensive – e.g. islands where all diesel has to be bought, or where operation would otherwise not possible – again favoring island or off-grid systems.

Compared to more complex and sophisticated tools the simple spreadsheet solution for the simulation of a storage supported PV generation shows promising results. The scenarios could be easily extended to allow for the integration of additional renewable energy generation systems such as wind or biogas. The focusing on the simple setup based on generation and load profiles for every 15 min for every day of the year will not only be possible with existing data gathered in real environments but is ideally positioned with the development of smart grid solutions where such load data are more easily available.

The insight into the energy flow management will allow in the future a better implementation of balancing strategies in such systems allowing the optimization of scheduling strategies. This can include dynamic energy prices in order to increase the validity of electricity storage systems in those scenarios. The presented solution is also meaningful in the case of large scale systems such as community storage systems. The combination of several households simply reduces the local load peaks which are difficult to accommodate and the actual aggregated load profile will be closer to the standardized load profiles available.

While additional incentive systems – such as the self-use compensation system in Germany – might influence the market, the expected lower price for storage systems and the better scalability will increase the applicability and feasibility of systems utilizing electric energy storage systems. The integration of storage systems into the overall energy management systems and the impact for the grid connection are a further challenge which needs more research to reach the next step in the implementation of decentralized renewable energy systems.

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Annexes

8.1 Power Generation

A considerable amount of the world's electricity is generated using steam turbine systems. Usually a boiler is used to raise steam which drives a steam turbine, also known as the prime mover, and the steam turbine in turn drives an electrical generator. Steam to drive these turbines is raised by burning fossil fuels or by nuclear power.

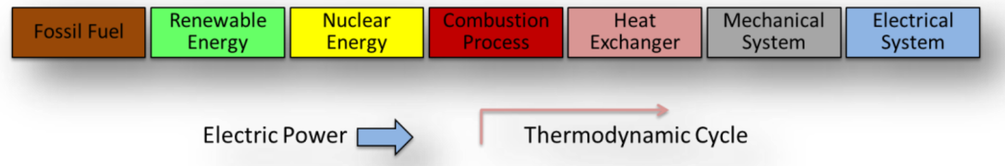

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Figure 64: Power generation key

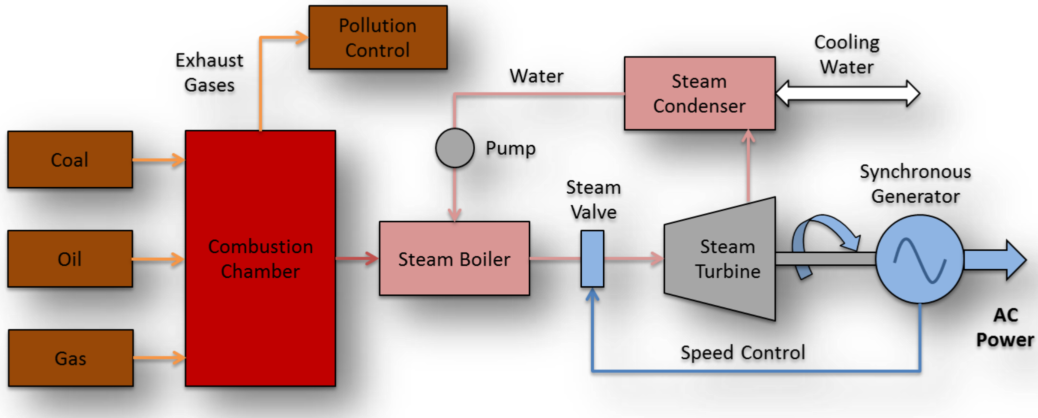

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Figure 65: Fossil Fuel Powered Steam Turbine Electricity Generation

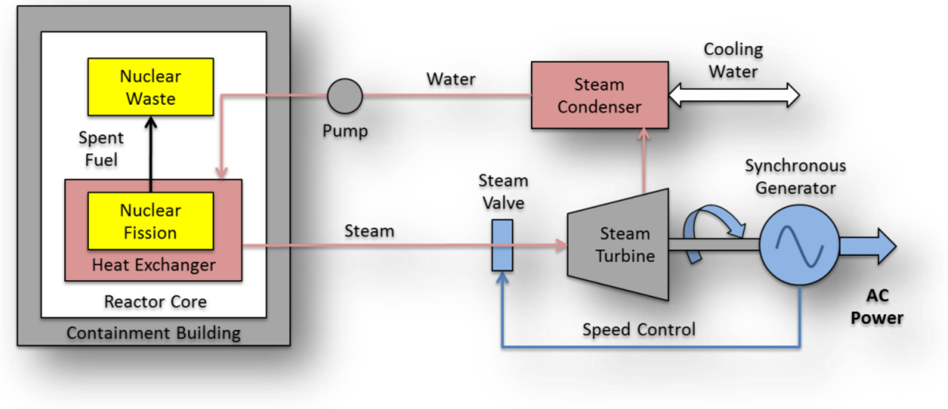

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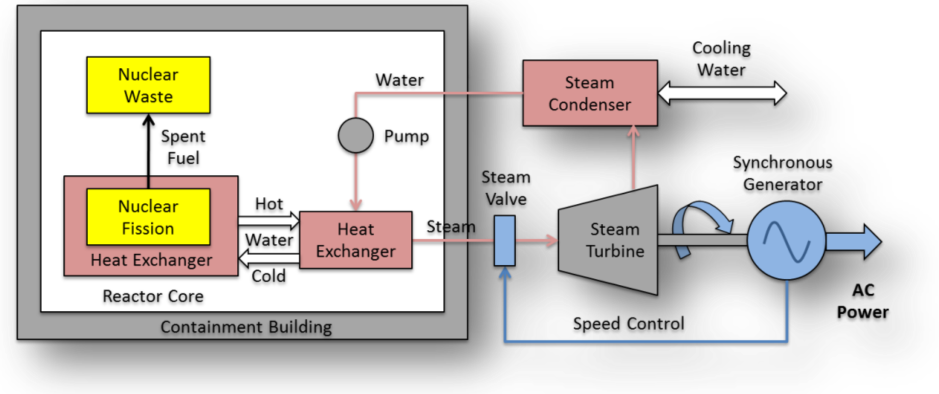
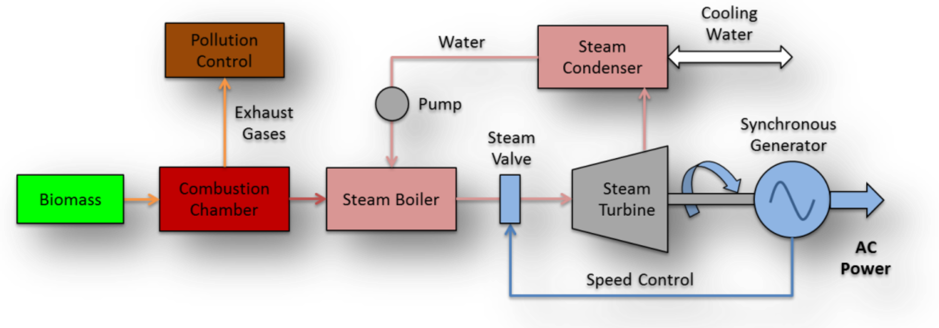
Figure 66: Electricity Generation by Nuclear Power



Source: based on http://www.mpoweruk.com/electrical_energy.htm

Figure 67: Electricity Generation by Nuclear Power (cont.)

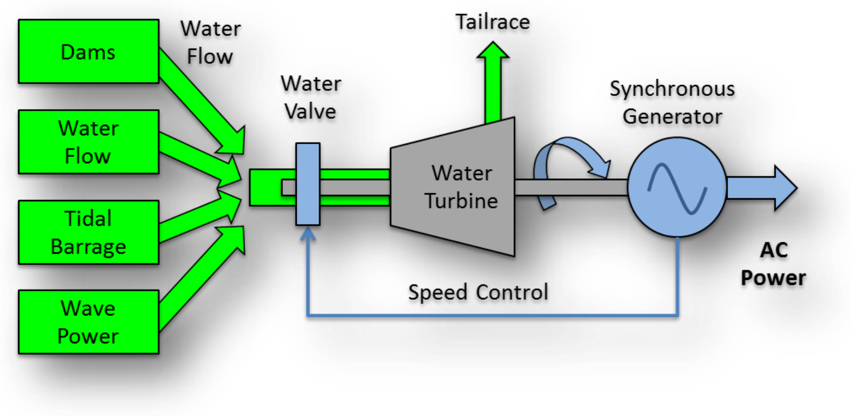
Even in the case of biomass power plant the overall principle of electricity generation remains the same. Biomass is the fuel burned in the biomass plant using a conventional steam turbine electricity generation.



Source: based on http://www.mpoweruk.com/electrical_energy.htm

Figure 68: Electricity Generation Powered by Biomass

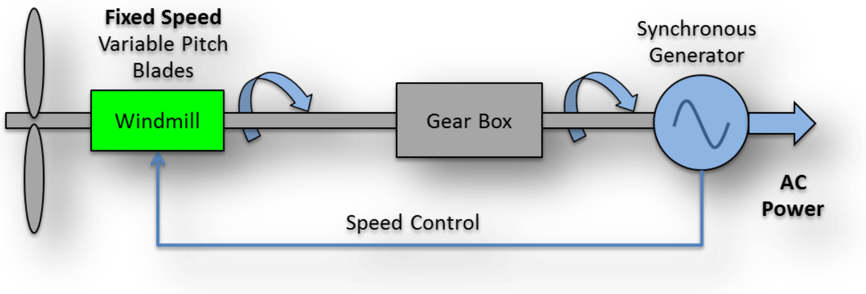
Hydro energy is available as potential energy from high heads of water retained in dams, and kinetic energy from current flow in rivers and tidal barrages.



Source: based on http://www.mpoweruk.com/electrical_energy.htm

Figure 69: Hydro Electric Power Generation

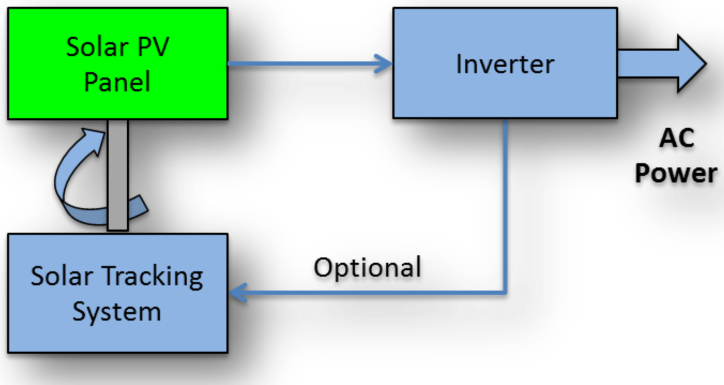
Windmills have been used for irrigation pumping and for milling grain since the 7th century AD (Wikipedia). Today a typical system employs a fixed speed rotor with three variable pitch blades. The rotor drives a synchronous generator through a gear box and the whole assembly is housed in a nacelle on top of a substantial on top of a concrete foundation.



Source: based on http://www.mpoweruk.com/electrical_energy.htm

Figure 70: Large Scale Wind Power System

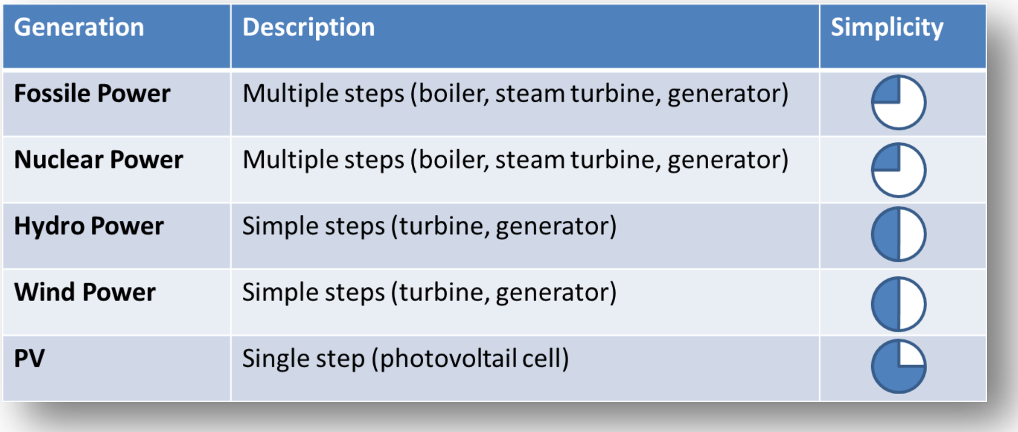
Solar voltaic power generation is the direct conversion of solar energy into electricity using photovoltaic cells. Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect.



Source: based on http://www.mpoweruk.com/electrical_energy.htm

Figure 71: Photovoltaic Electric Power Generation

Note that in this case no moving parts are involved. There is no conversion of chemical energy into heat energy, no conversion of heat energy into kinetic energy, and no conversion of kinetic energy into electricity. There is the need for managing such a system and the integration into the grid is sometimes a challenge.



Generation	Description	Simplicity
Fossile Power	Multiple steps (boiler, steam turbine, generator)	◔
Nuclear Power	Multiple steps (boiler, steam turbine, generator)	◔
Hydro Power	Simple steps (turbine, generator)	◑
Wind Power	Simple steps (turbine, generator)	◑
PV	Single step (photovoltail cell)	◕

Table 6: Electricity Generation Simplicity

If compared to the other electricity generation options, PV is the most simplistic one. The system architecture of a PV system, while considered high-tech, is very simple. The simplistic nature of PV systems means that also maintenance of a PV system is simple. Simplicity also ensures reliability and a long lifetime.

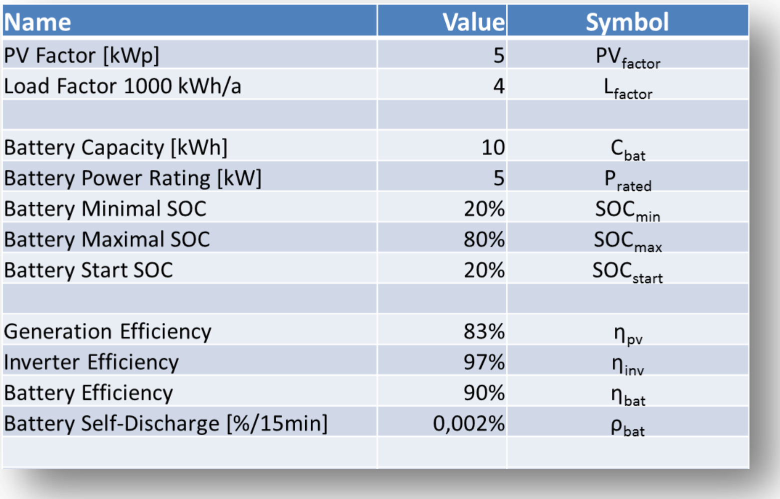
There are solar driven power plants - concentrating solar power plants (CSP) – where the typical conversion cycle is used. However, those types of solar power plants are similar to the conventional steam turbine electricity generation – they just use the sun to collect the heat to generate steam to drive the electricity production.

The steam turbine generating plants used to supply the grid's base load are typically deployed only as large scale installations requiring special precautions because of their large physical size and the high voltages and currents involved. Also large scale hydro power systems and wind farms (e.g. offshore) are usually not close to the location of final use and need the power grid for transmission and distribution.

Smaller scale systems use a variety of alternative generation schemes which can also be tailored for domestic use. The main types of domestic electricity generation are photovoltaic generation (PV) and small wind turbines. Electricity generation by sterling engines or fuel cells is a possible future option.

8.2 Simulation Results

All simulation results shown are for the following basic input data:



Name	Value	Symbol
PV Factor [kWp]	5	PV_{factor}
Load Factor 1000 kWh/a	4	L_{factor}
Battery Capacity [kWh]	10	C_{bat}
Battery Power Rating [kW]	5	P_{rated}
Battery Minimal SOC	20%	SOC_{min}
Battery Maximal SOC	80%	SOC_{max}
Battery Start SOC	20%	SOC_{start}
Generation Efficiency	83%	η_{pv}
Inverter Efficiency	97%	η_{inv}
Battery Efficiency	90%	η_{bat}
Battery Self-Discharge [%/15min]	0,002%	ρ_{bat}

Table 7: Simulation Data Input

The PV generation is calculated from the PVGIS data (average daily irradiation based on the solar radiation database: PVGIS-CMSAF).

8.2.1 Scenario without battery

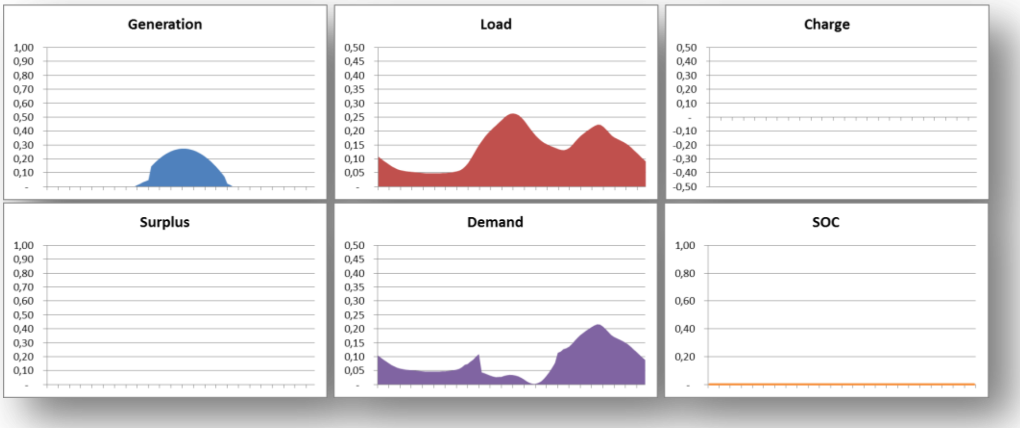


Figure 72: 1st January - all values in kWh

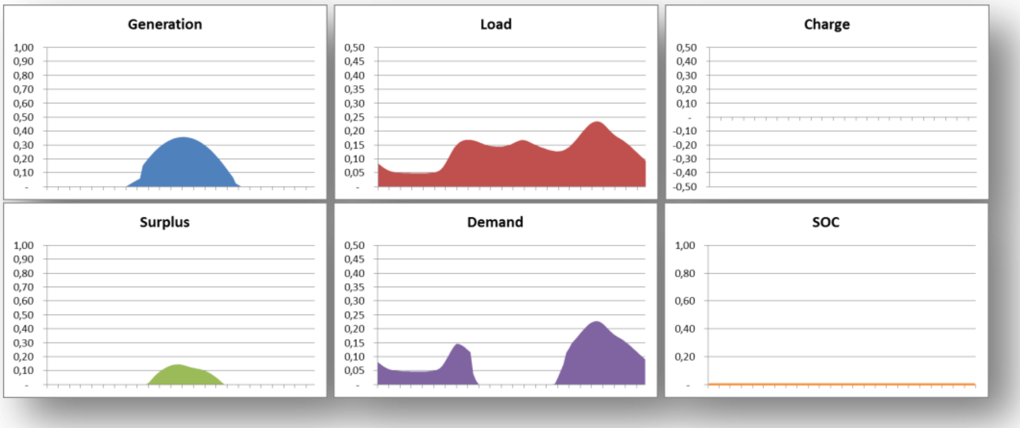


Figure 73: 1st February - all values in kWh

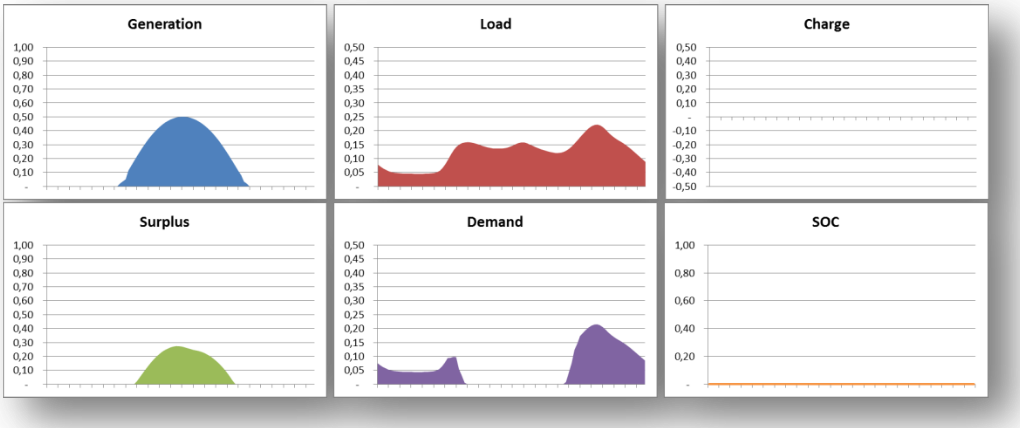


Figure 74: 1st March - all values in kWh

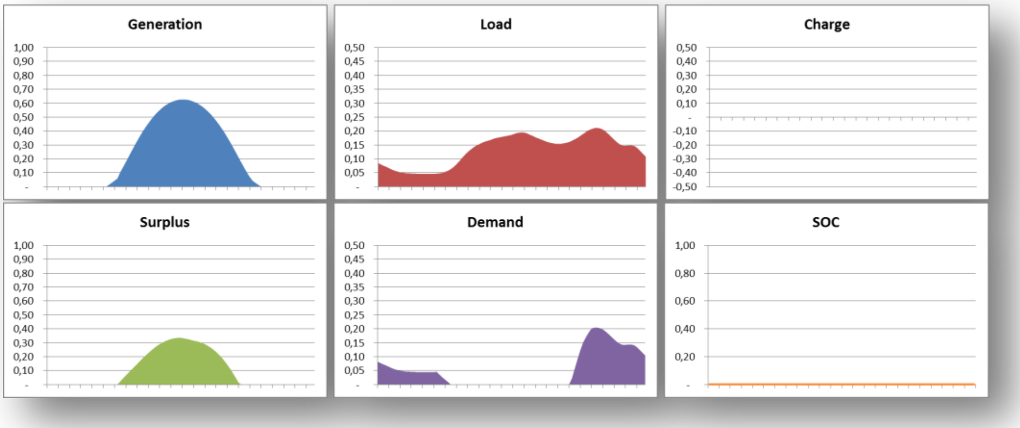


Figure 75: 1st April - all values in kWh

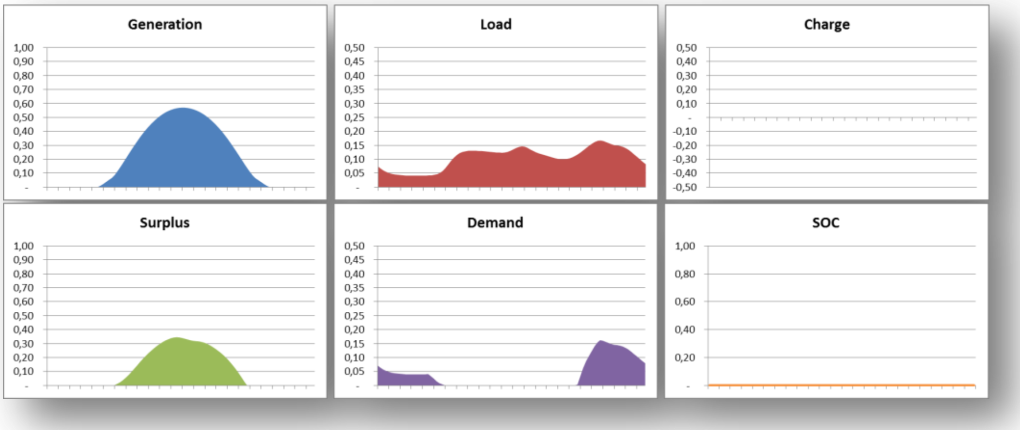


Figure 76: 1st May - all values in kWh

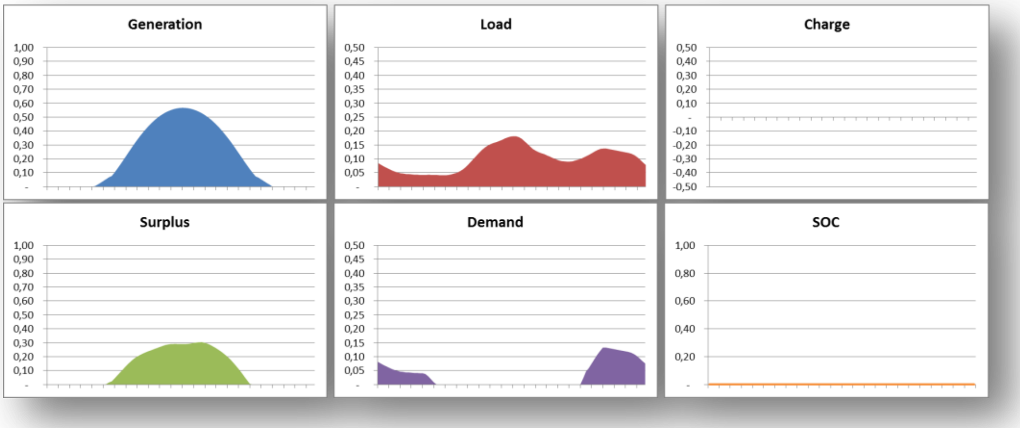


Figure 77: 1st June - all values in kWh

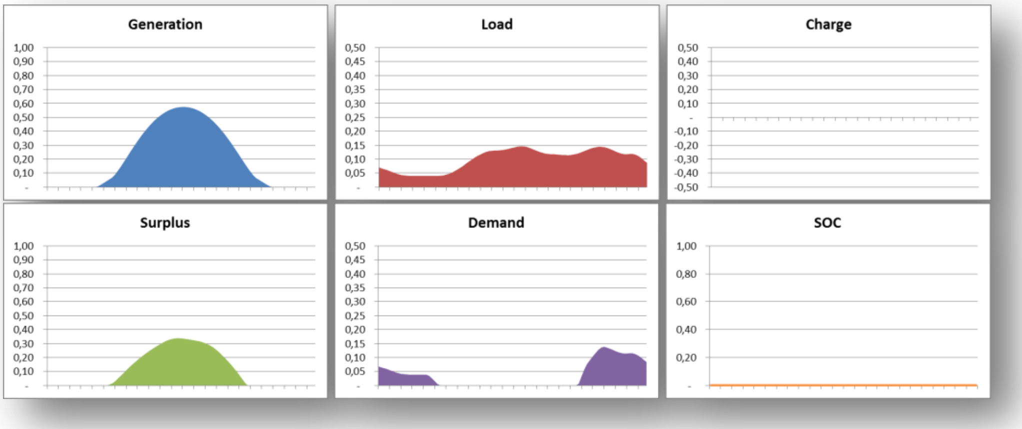


Figure 78: 1st July - all values in kWh

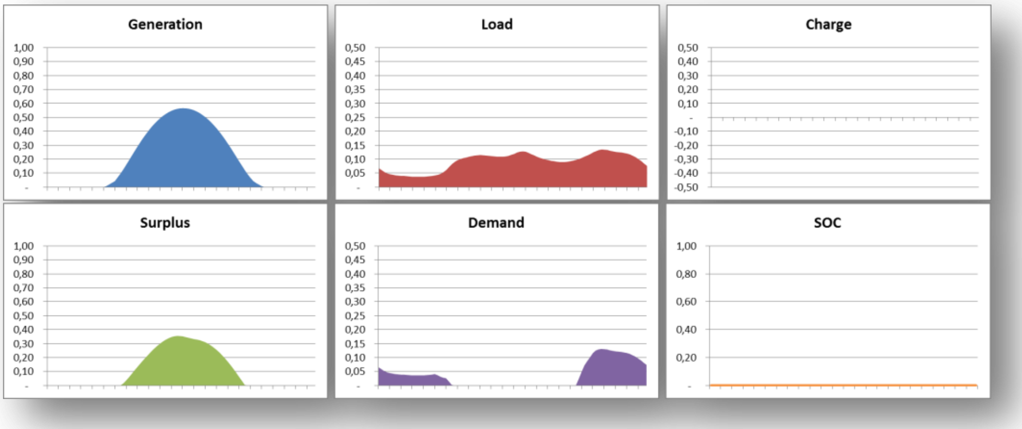


Figure 79: 1st August - all values in kWh

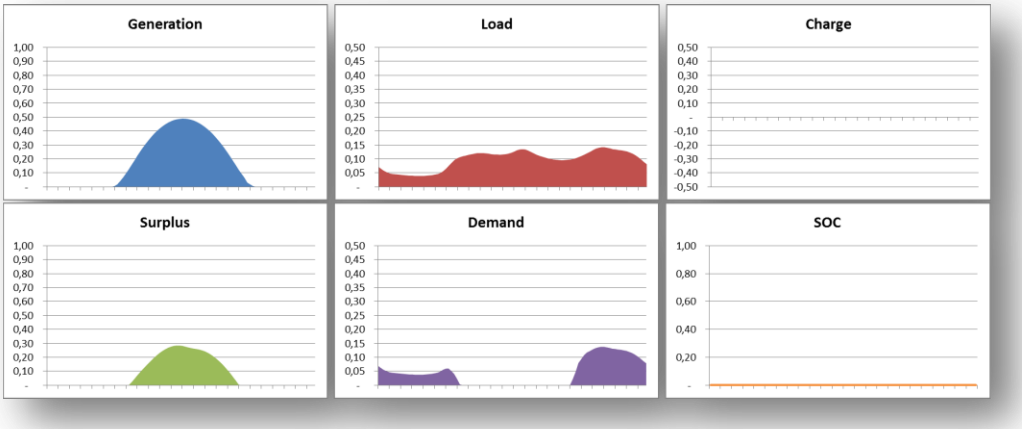


Figure 80: 1st September - all values in kWh

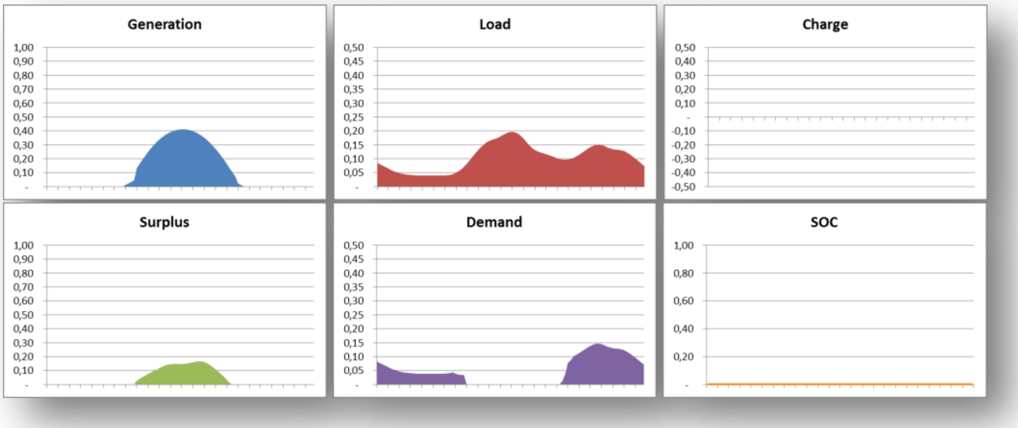


Figure 81: 1st October - all values in kWh

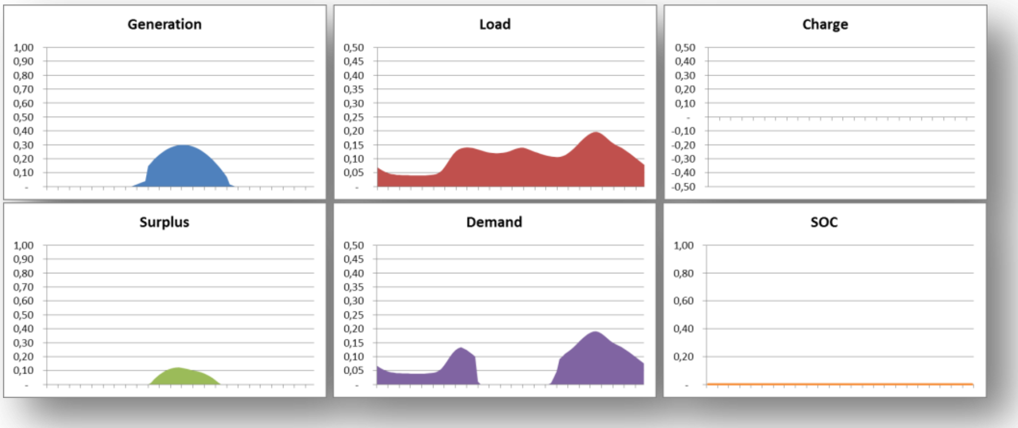


Figure 82: 1st November - all values in kWh

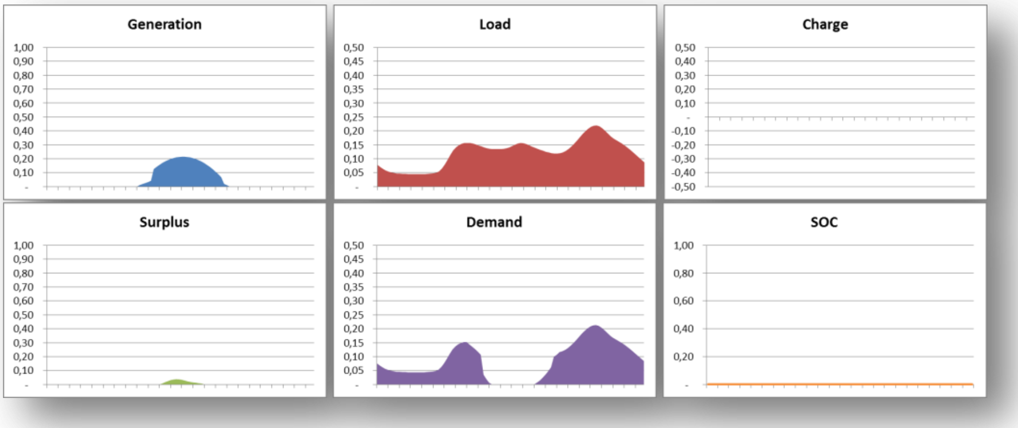


Figure 83: 1st December - all values in kWh

8.2.2 Scenario with 10 kWh battery

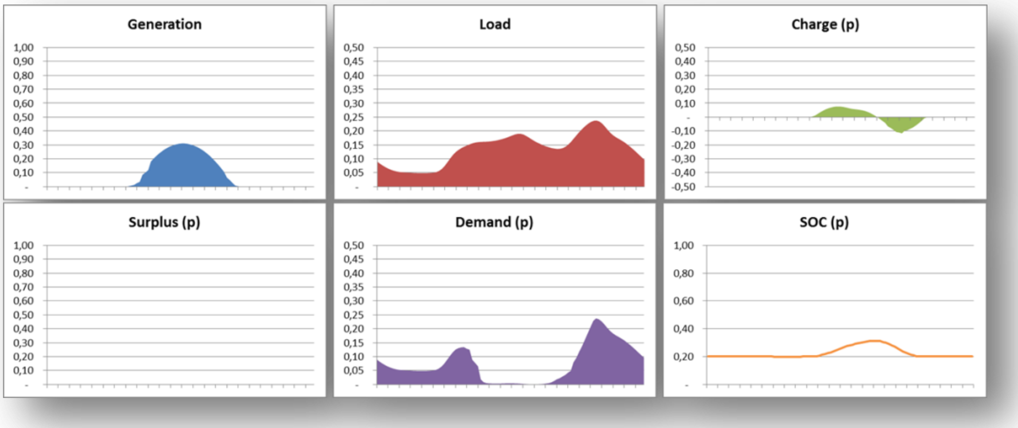


Figure 84: 1st January - all values in kWh, SOC 0-1

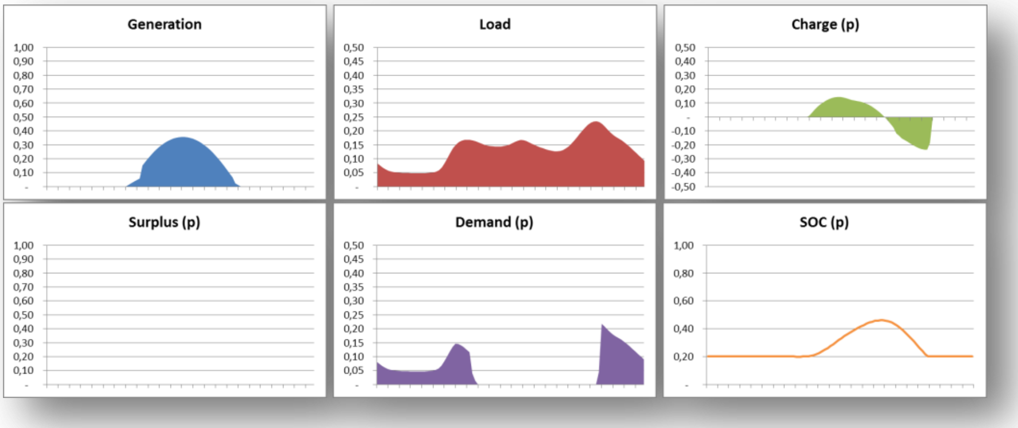


Figure 85: 1st February - all values in kWh, SOC 0-1

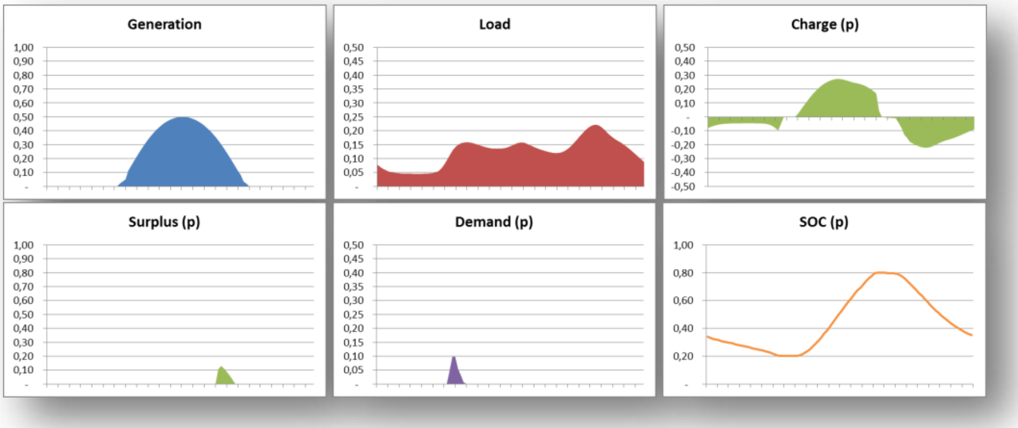


Figure 86: 1st March - all values in kWh, SOC 0-1

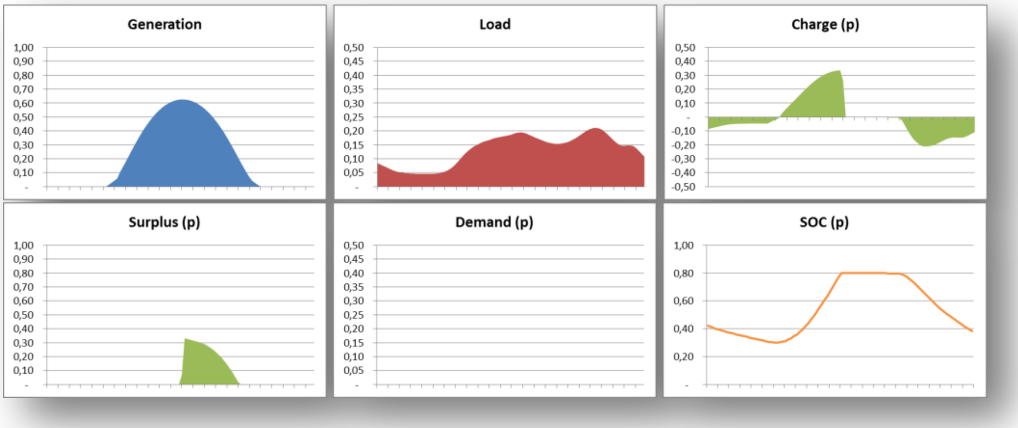


Figure 87: 1st April - all values in kWh, SOC 0-1

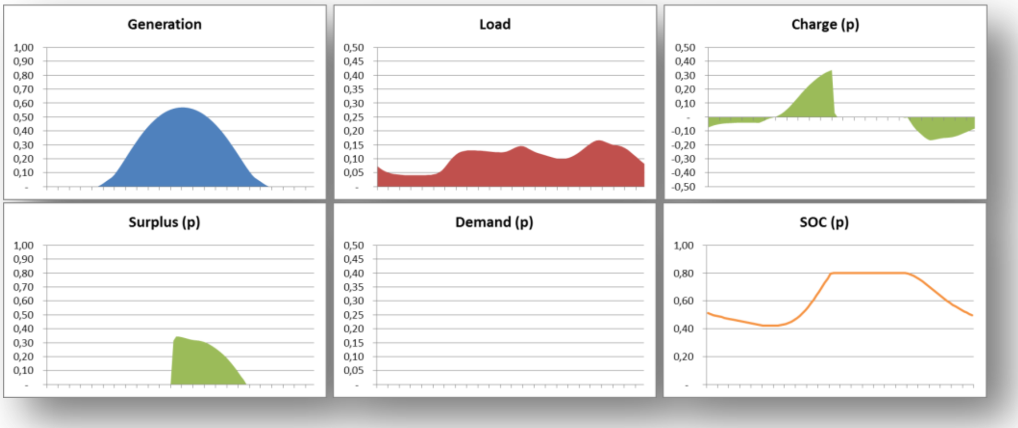


Figure 88: 1st May - all values in kWh, SOC 0-1

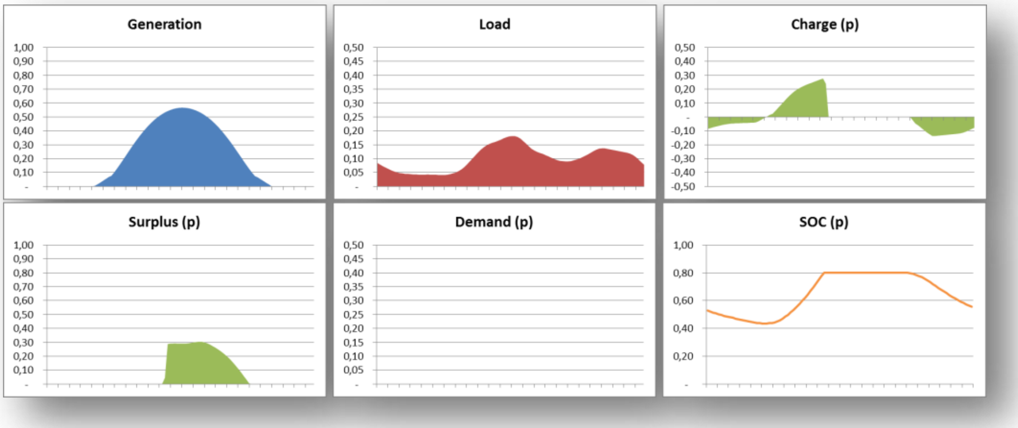


Figure 89: 1st June - all values in kWh, SOC 0-1

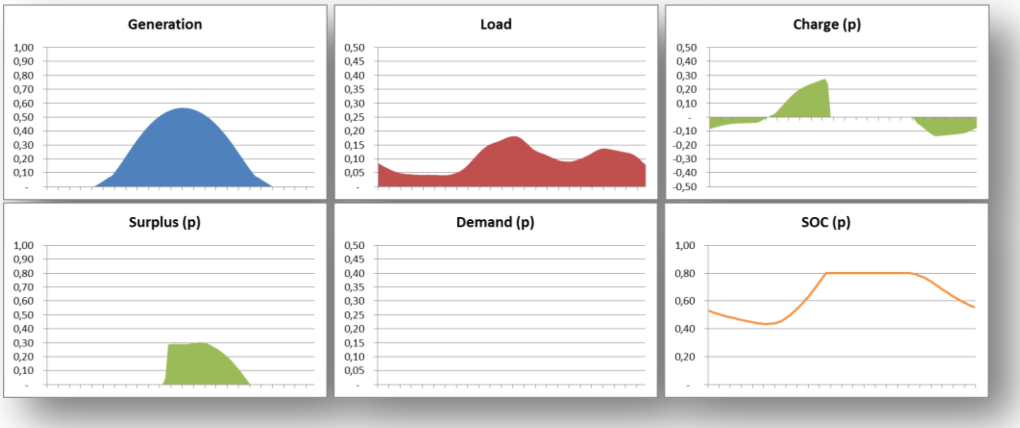


Figure 90: 1st July - all values in kWh, SOC 0-1

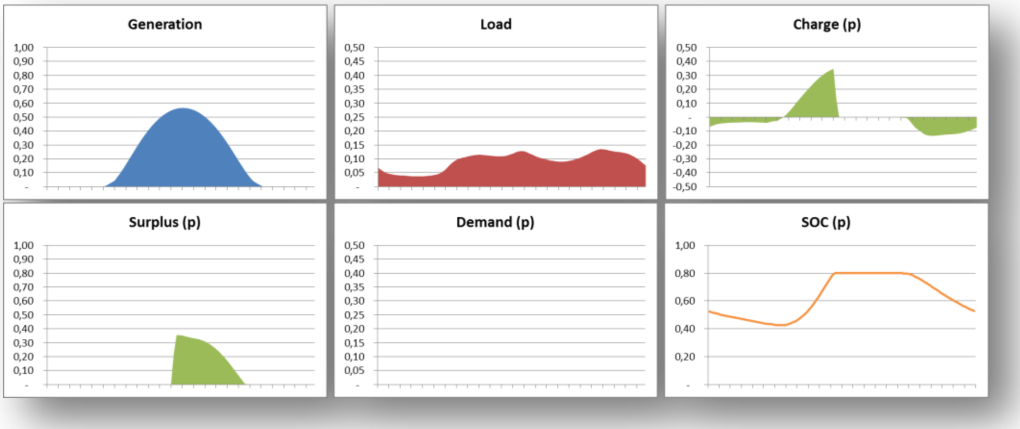


Figure 91: 1st August - all values in kWh, SOC 0-1

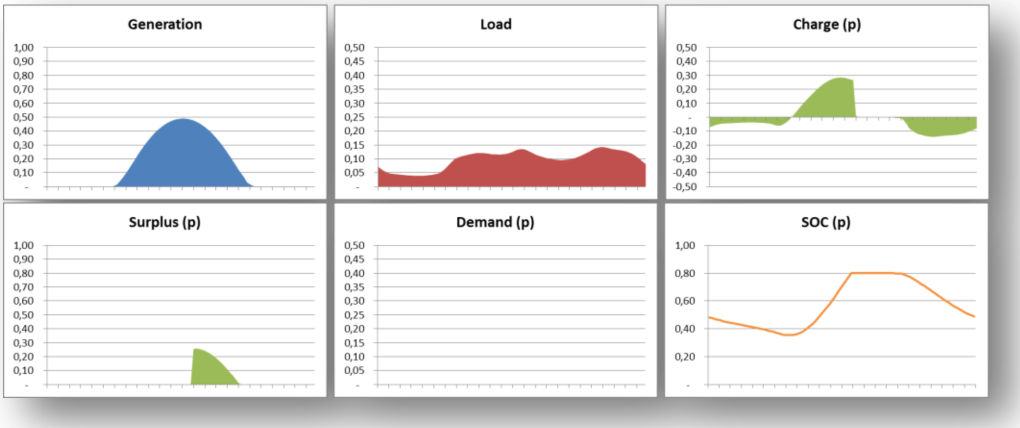


Figure 92: 1st September - all values in kWh, SOC 0-1

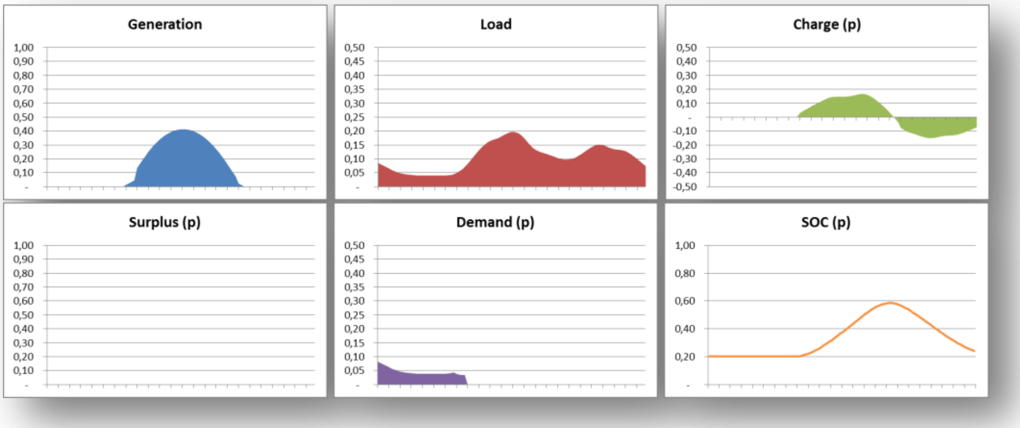


Figure 93: 1st October - all values in kWh, SOC 0-1

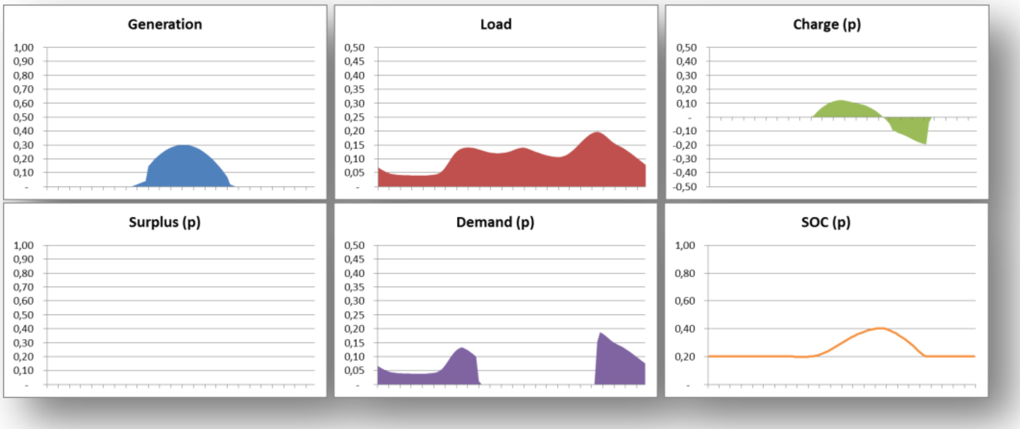


Figure 94: 1st November - all values in kWh, SOC 0-1

Figure 95: 1st December - all values in kWh, SOC 0-1

8.2.3 Scenario with 10 kWh battery – Monthly Average

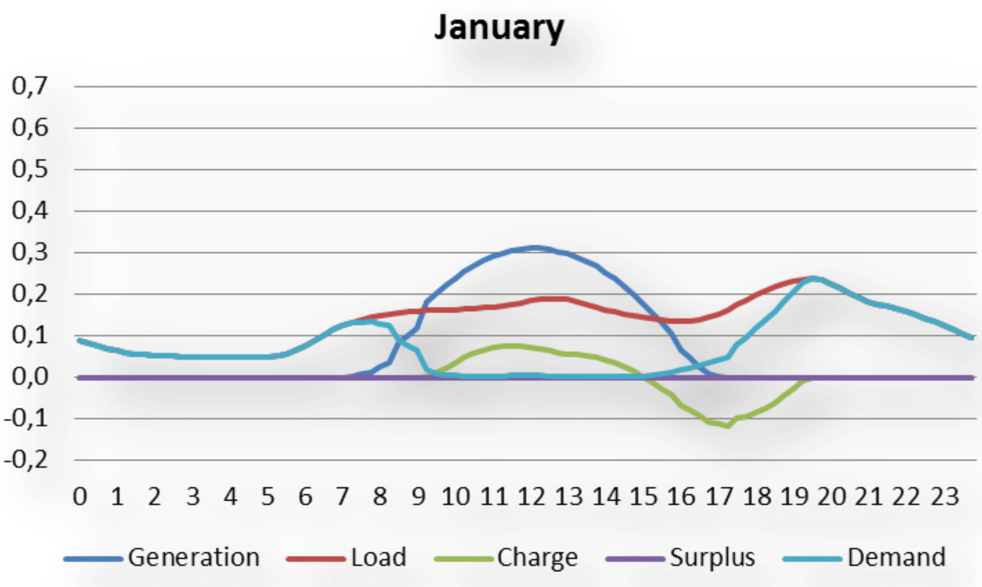


Figure 96: January - average values in kWh, SOC 0-1

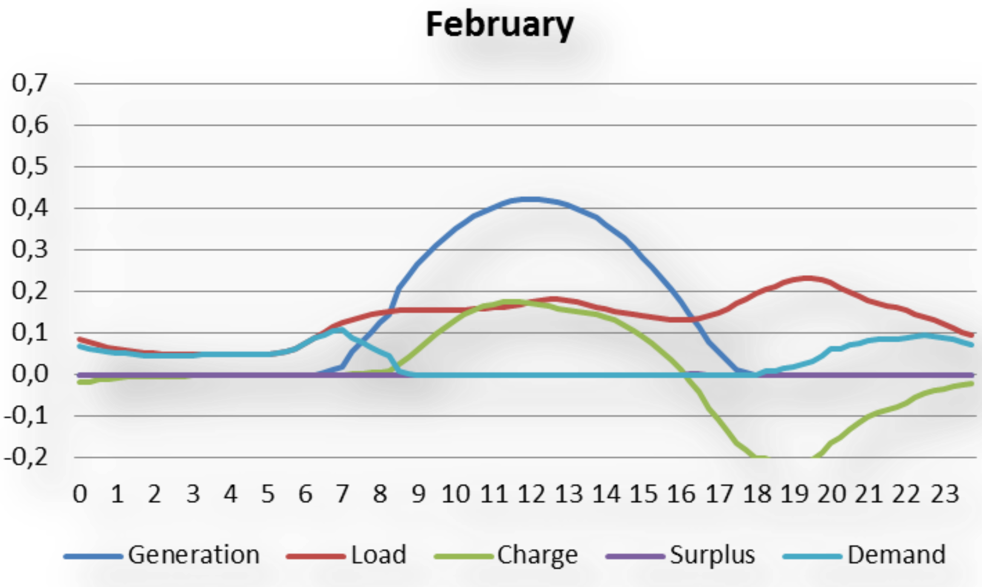


Figure 97: February - average values in kWh, SOC 0-1

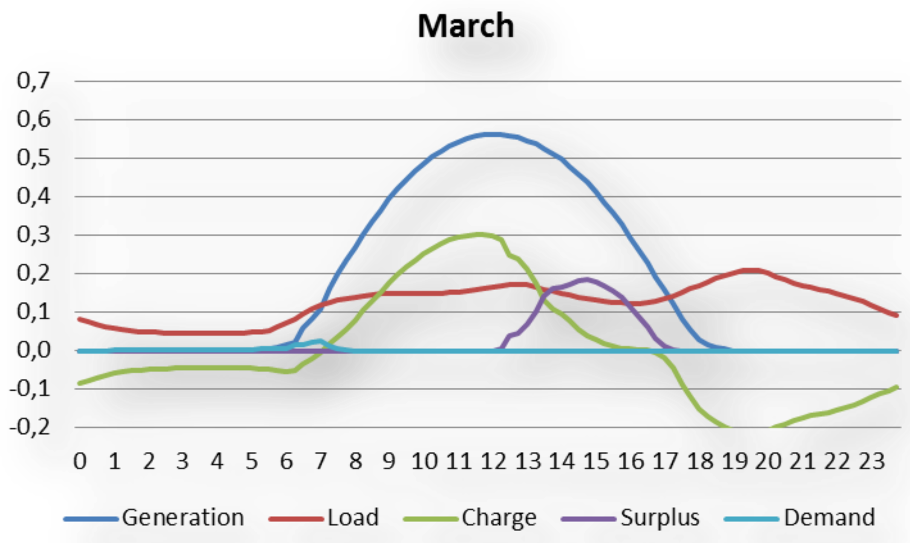


Figure 98: March - average values in kWh, SOC 0-1

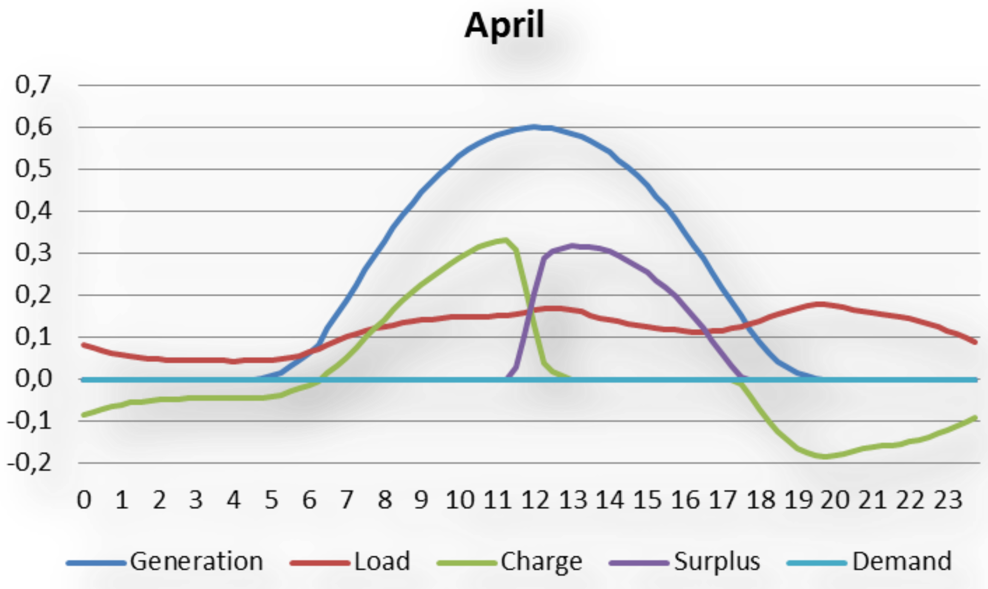


Figure 99: April - average values in kWh, SOC 0-1

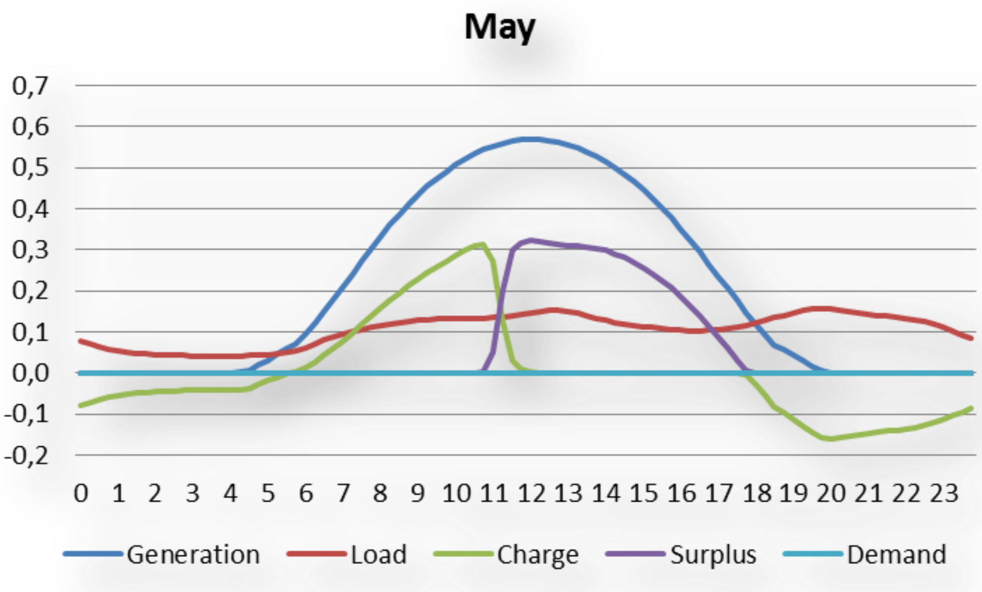


Figure 100: May - average values in kWh, SOC 0-1

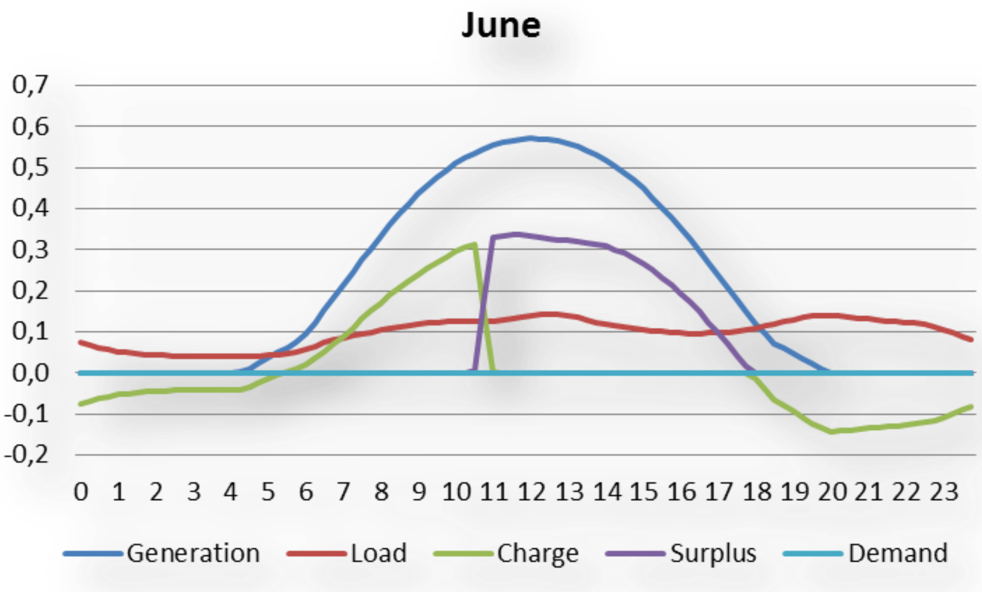


Figure 101: June - average values in kWh, SOC 0-1

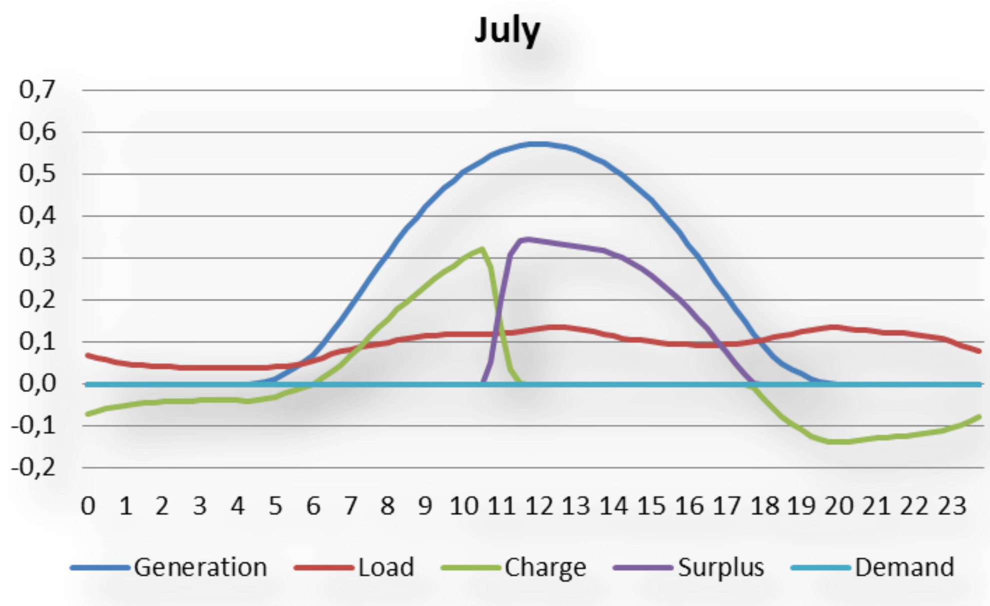


Figure 102: July - average values in kWh, SOC 0-1

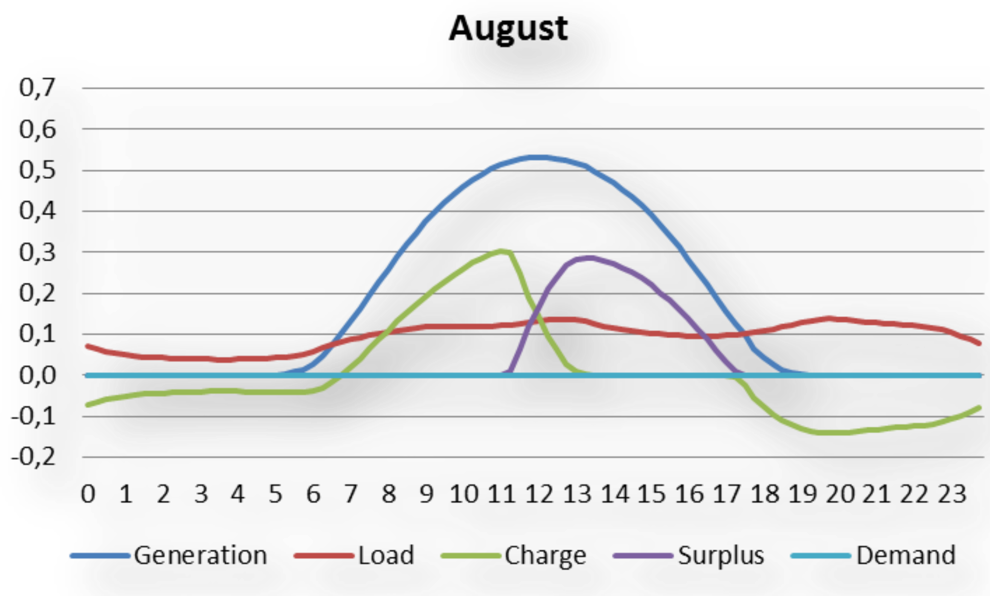


Figure 103: August - average values in kWh, SOC 0-1

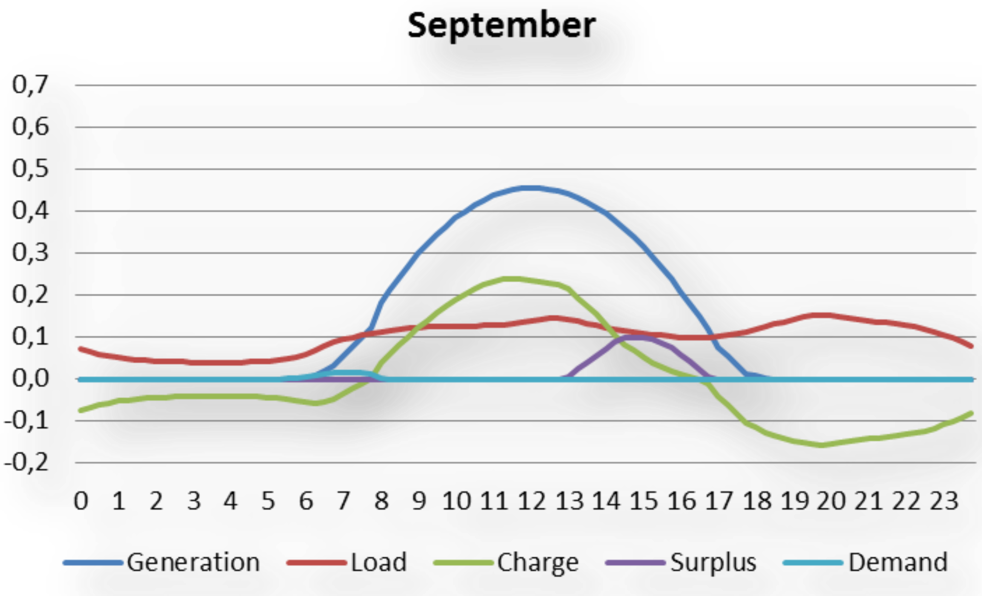


Figure 104: September - average values in kWh, SOC 0-1

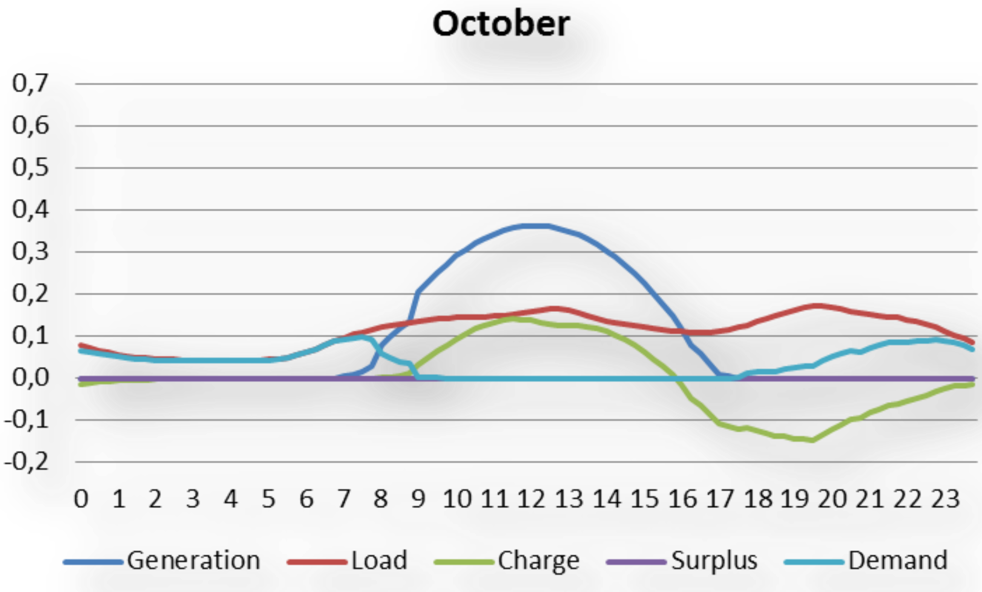


Figure 105: October - average values in kWh, SOC 0-1

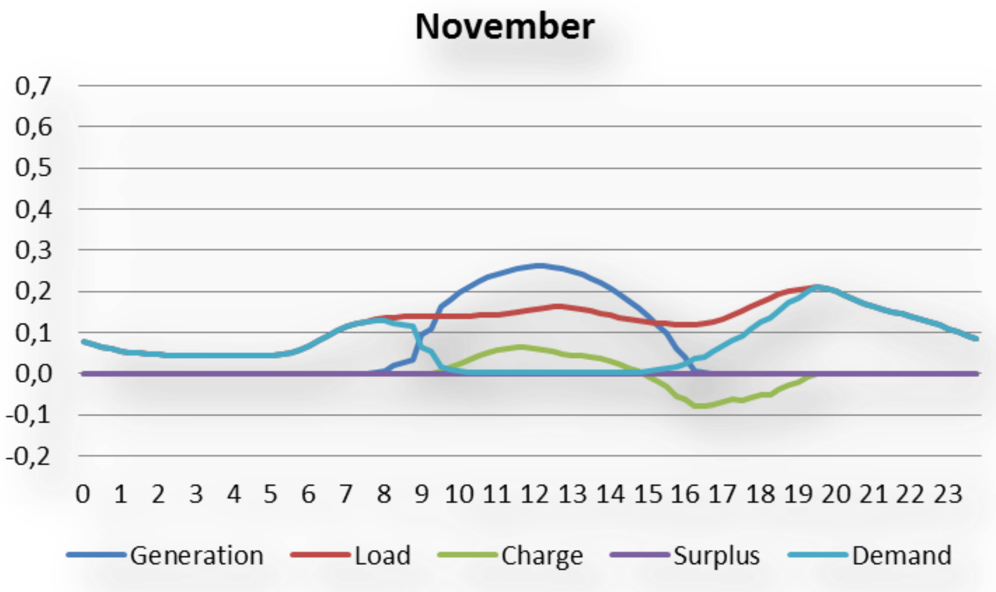


Figure 106: November - average values in kWh, SOC 0-1

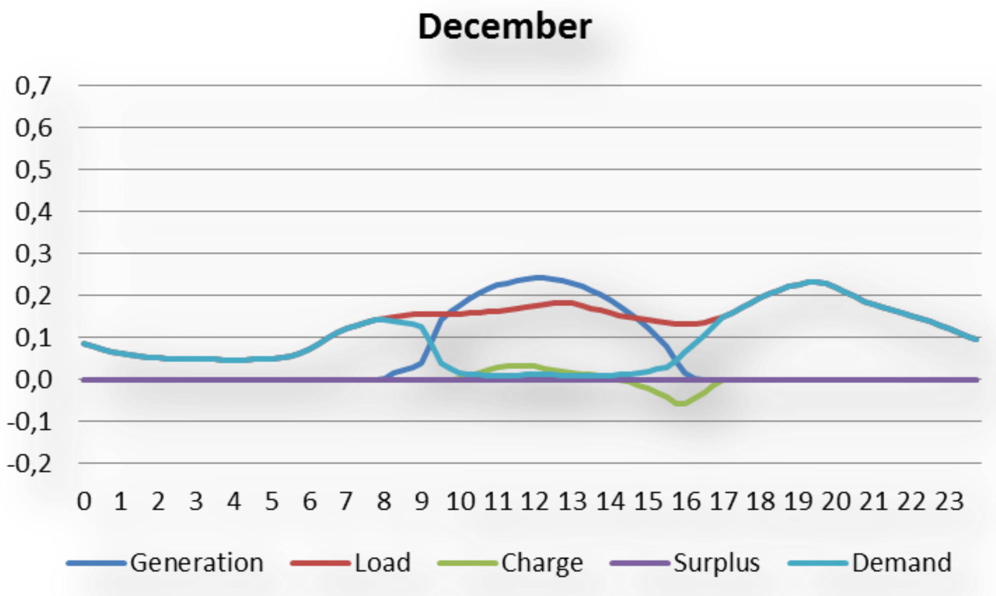


Figure 107: December - average values in kWh, SOC 0-1

8.3 Simulation Implementation

Microsoft Excel 2010 is used to implement the simulation and reporting tool. Several spreadsheets are used to capture input and calculated data.

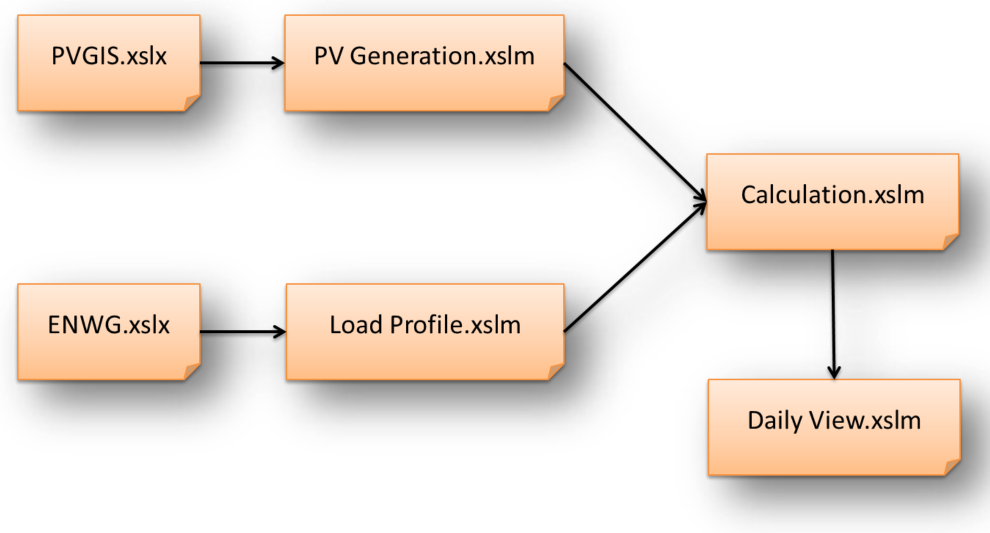


Figure 108: Simulation Spreadsheets

The basic input data are hold in the *PVGIS.xslx* and *ENWG.xslx* respectively. Two further macro enabled spreadsheets are used to calculate the actual PV generated energy - *PV Generation.xlsm* - and reformatting the supplied standard load profile data - *Load Profile.xlsm*. The actual calculation is done in the *Calculation.xslm* spreadsheet. Finally the *Daily View.xslm* sheet is used to generate charts of daily data for additional reporting purposes.

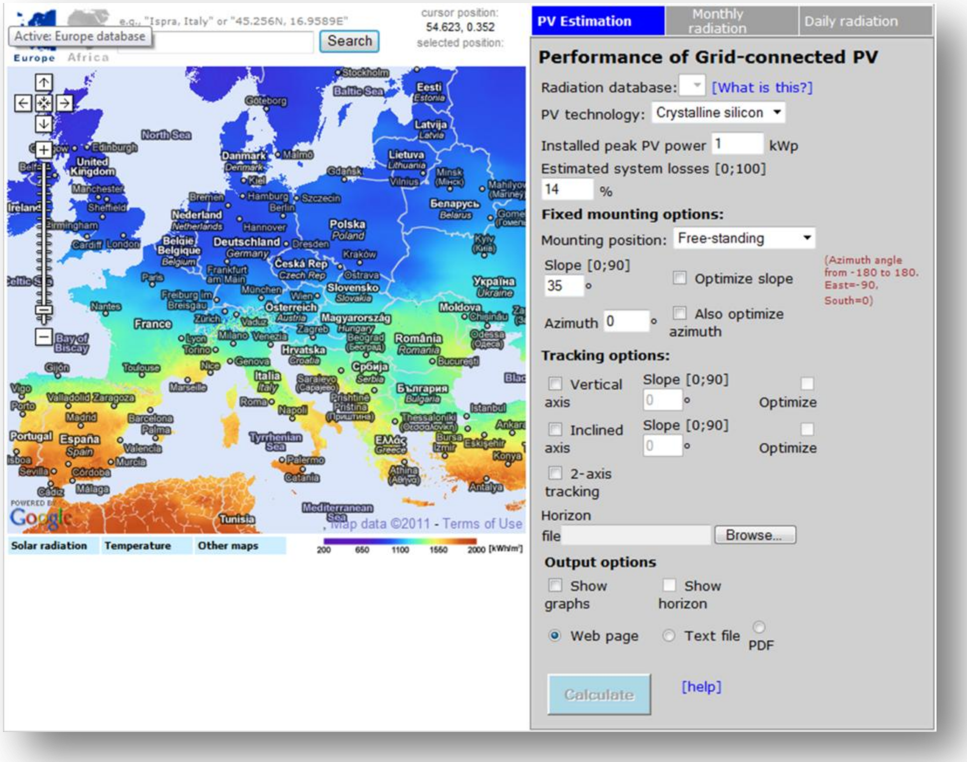
8.3.1 PVGIS.xslx

The interactive PV charts for Europe from the PVGIS website are used to get the irradiation data.

8.3.1.1 Solar irradiation data utility

The monthly and yearly averages of global irradiation at horizontal and inclined surfaces, as well as other climatic and PV-related data are provided. The location is selected and the module type, the module inclination and the orientation (azimuth) have to be entered. The daily profiles of clear-sky and real-sky irradiances for every month can be requested. The calculation takes the shadowing by local terrain features into account. Finally the monthly and yearly potential electricity generation

E [kWh] of a PV configuration with defined modules inclination and orientation can be accessed.



Performance of Grid-connected PV

Radiation database: [What is this?]
PV technology: Crystalline silicon
Installed peak PV power 1 kWp
Estimated system losses [0;100] 14 %

Fixed mounting options:
Mounting position: Free-standing
Slope [0;90] 35 ° ☐ Optimize slope
Azimuth 0 ° ☐ Also optimize azimuth
(Azimuth angle from -180 to 180. East=-90, South=0)

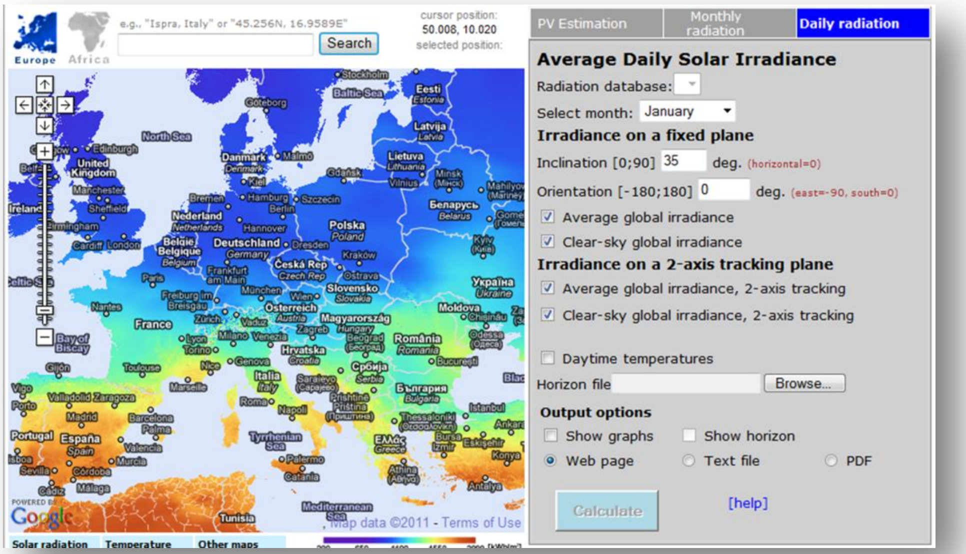
Tracking options:
☐ Vertical axis Slope [0;90] 0 ° ☐ Optimize
☐ Inclined axis Slope [0;90] 0 ° ☐ Optimize
☐ 2-axis tracking
Horizon file Browse...

Output options
☐ Show graphs ☐ Show horizon
● Web page ○ Text file ○ PDF

Calculate [help]

Figure 109: PV Estimation

The PV estimation is used to compare the calculation of the simulation tool with the online calculation. The actual data used as an input are the daily irradiation data for every month.



Average Daily Solar Irradiance
Radiation database:
Select month: January
Irradiance on a fixed plane
Inclination [0;90] 35 deg. (horizontal=0)
Orientation [-180;180] 0 deg. (east=-90, south=0)
☑ Average global irradiance
☑ Clear-sky global irradiance
Irradiance on a 2-axis tracking plane
☑ Average global irradiance, 2-axis tracking
☑ Clear-sky global irradiance, 2-axis tracking
☐ Daytime temperatures
Horizon file
Output options
☐ Show graphs ☐ Show horizon
● Web page ○ Text file ○ PDF

Figure 110: Daily Radiation

The output from the website (output option *Web page* selected) is simply pasted into the *PVGIS.xsls* workbook as sheet content for every month. Note that the actual peak power used for all calculation is 1 kWp.

8.3.2 PV Generation.xslm

All irradiation data for every month from the *PVGIS.xslx* workbook are used as input for the PV generation calculation. The daily data from the PVGIS website are used to interpolate generation data for every day of the year. The actual spreadsheets used have 96 rows for the data in 15 min intervals and 356 columns for every day of the year resulting in 35040 cells.

The following VBA script code is used to calculate the PC generation:

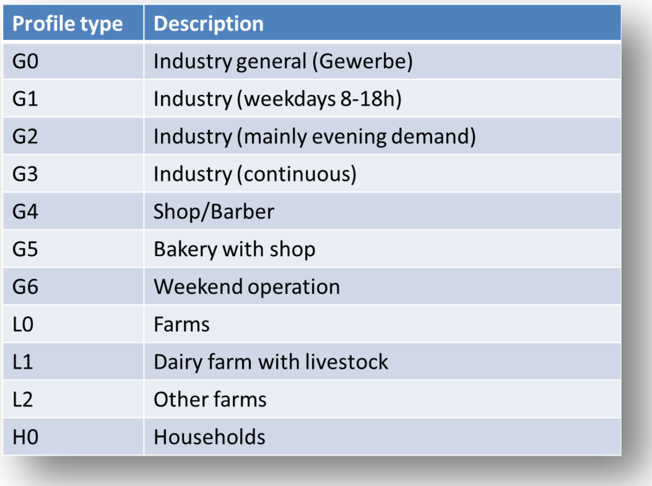
```
' <copyright file="PV Generation.xlsm" company="Dr. Peter Trimmel">
'     Copyright (c) 2011 Dr. Peter Trimmel. All rights reserved.
' </copyright>
' <module>PVCalcModule</module>
' <summary>
'     The PVGIS irradiation values are used to calculate the
'     actual power output. The calculation factors and formula
'     are from the paper "Mapping the performance of PV modules
'     of different types", Thomal Huld, Ralf Gottschalg, Hans
'     Georg Beyer, Marco Topic, 2009
'     (retrieved from the PVGIS website)
' </summary>
'
' Global constants
Const ROW_OFFSET = 4
Const COL_OFFSET = 3

' Global factors
Dim k1 As Double
```

```
Dim k2 As Double
Dim k3 As Double
Dim k4 As Double
Dim k5 As Double
Dim k6 As Double
Dim ct As Double

' Routine to update the energy production sheet (PVGIS)
'
Sub UpdateEnergyPV()
    ' index variables
    Dim row As Integer
    Dim col As Integer
    Dim i As Integer
    ' main variables
    Dim power As Double
    Dim irradiance As Double
    Dim temperature As Double

    ' setup timer
    Dim start As Single
    Dim finish As Single
    Dim elapsed As Single

    start = Timer

    Application.ScreenUpdating = False
    Application.DisplayStatusBar = True
    Application.Calculation = xlCalculationManual

    ' read global parameters
    power = ThisWorkbook.Sheets("Data").Range("Power_Rating").Value
    k1 = ThisWorkbook.Sheets("Data").Range("Factor_1").Value
    k2 = ThisWorkbook.Sheets("Data").Range("Factor_2").Value
    k3 = ThisWorkbook.Sheets("Data").Range("Factor_3").Value
    k4 = ThisWorkbook.Sheets("Data").Range("Factor_4").Value
    k5 = ThisWorkbook.Sheets("Data").Range("Factor_5").Value
    k6 = ThisWorkbook.Sheets("Data").Range("Factor_6").Value
    ct = ThisWorkbook.Sheets("Data").Range("Temperature_Coefficient").Value

    For col = COL_OFFSET To 364 + COL_OFFSET
        For row = ROW_OFFSET To 95 + ROW_OFFSET
            Application.StatusBar = "EPV[" & row & "," & col & "]"

            temperature = ThisWorkbook.Sheets("T (Year)").Cells(row, col).Value
            irradiance = ThisWorkbook.Sheets("G (Year)").Cells(row, col).Value
            ThisWorkbook.Sheets("P (Year)").Cells(row, col).Value = _
                                power * CalculatePower(irradiance, temperature)
            irradiance = ThisWorkbook.Sheets("Gd (Year)").Cells(row, col).Value
            ThisWorkbook.Sheets("Pd (Year)").Cells(row, col).Value = _
                                power * CalculatePower(irradiance, temperature)
            irradiance = ThisWorkbook.Sheets("Gc (Year)").Cells(row, col).Value
            ThisWorkbook.Sheets("Pc (Year)").Cells(row, col).Value = _
                                power * CalculatePower(irradiance, temperature)
        Next
    Next

    Application.Calculation = xlCalculationAutomatic
    Application.ScreenUpdating = True
    Application.StatusBar = False
    Application.Calculate

    finish = Timer
    elapsed = Format(finish - start, "Fixed")
    ThisWorkbook.Sheets("Data").Range("Elapsed_Time").Value = elapsed

End Sub

' Function to calculate the power value (PVGIS)
'
' Parameter
'     irradiance    - Global irradiance PV in W/m
'     temperature   - Ambient temperature in C
'
' Return Value
'     power         - Generated power at normalized Pstc = 1 W
'
```

```
Function CalculatePower(irradiance As Double, temperature As Double) As Double
    Dim G As Double
    Dim T As Double
    Dim ln As Double
    Dim eff As Double

    CalculatePower = 0

    If irradiance > 0 Then
        G = irradiance / 1000
        T = temperature + ct * irradiance - 25
        ln = Log(G)
        eff = 1 + k1 * ln + k2 * ln * ln + T * (k3 + k4 * ln + k5 * ln * ln + k6 * T)
        If eff < 0 Then G = 0
        CalculatePower = G * eff
    End If

End Function
```

8.3.3 ENWG.xslx

The input spreadsheet for the standardized load profiles contains all data from the ENWG. The following load profiles are available:



Profile type	Description
G0	Industry general (Gewerbe)
G1	Industry (weekdays 8-18h)
G2	Industry (mainly evening demand)
G3	Industry (continuous)
G4	Shop/Barber
G5	Bakery with shop
G6	Weekend operation
L0	Farms
L1	Dairy farm with livestock
L2	Other farms
H0	Households

Source: Standardlastprofil - Wikipedia (Standardlastprofil, 2011)

Table 8: Standard ENWG Profile Types

In this study the household profile H0 is used as data input. Note that this data set includes data points for every day of the year. The selected data can be modified to a specific load profile if more detailed data based on load monitoring is available. All calculations shown here are based on the selected H0 (Households) load profile.

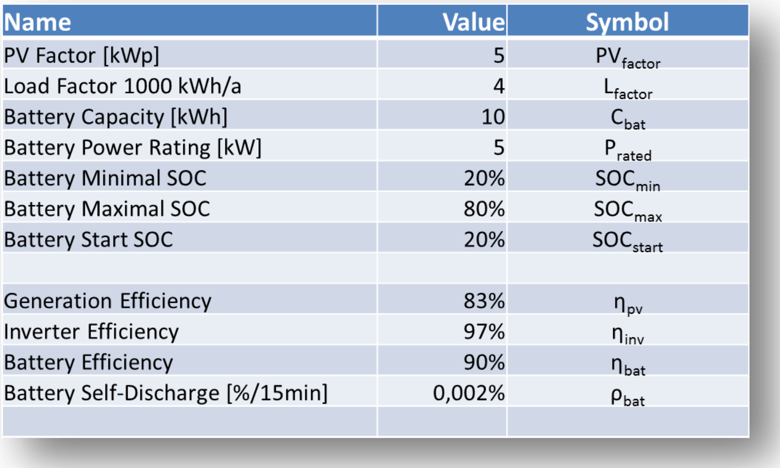
8.3.4 Load Profile.xslm

This macro enable spreadsheet is just combining the load data into a 96 rows by 356 columns. The following VBA script code is used to re-arrange the load data:

```
' <copyright file="Load Profile.xlsm" company="Dr. Peter Trimmel">
'     Copyright (c) 2011 Dr. Peter Trimmel. All rights reserved.
' </copyright>
' <module>LoadCalcModule</module>
' <summary>
'     The ENWG spreadsheet contains load data for every 15 min
'     in one large column. The load data are reordered into
'     daily values for all days in a year for further processing.
' </summary>
'
' Global constants
Const ROW_OFFSET = 3
Const COL_OFFSET = 2
Const DATA_OFFSET = 4
Const COL_DATA = 2

' Routine to update the load profile sheet
'
Sub UpdateLoad()
    ' main variables
    Dim row As Integer
    Dim col As Integer
    Dim index As Integer
    Dim count As Long
    Dim data As Worksheet

    ' setup timer
    Dim start As Single
    Dim finish As Single
    Dim elapsed As Single

    start = Timer

    Application.ScreenUpdating = False
    Application.DisplayStatusBar = True
    Application.Calculation = xlCalculationManual

    For index = 1 To Workbooks.count
        If Workbooks(index).Name = "ENWG.xls" Then
            Set data = Workbooks(index).Sheets(1)
            count = DATA_OFFSET

            For col = 1 To 365
                For row = 1 To 96
                    Application.StatusBar = "Load[" & row & "," & col & "]"
                    ThisWorkbook.Sheets("Load (Year)").Cells(row + ROW_OFFSET, _
                                     col + COL_OFFSET).Value = _
                                     data.Cells(count, COL_DATA).Value * 0.25

                    count = count + 1
                Next
            Next

        End If
    Next

    Application.Calculation = xlCalculationAutomatic
    Application.ScreenUpdating = True
    Application.StatusBar = False
    Application.Calculate

    finish = Timer
    elapsed = Format(finish - start, "Fixed")
    ThisWorkbook.Sheets("Data").Range("Elapsed_Time").Value = elapsed

End Sub
```

8.3.5 Calculation.xslm

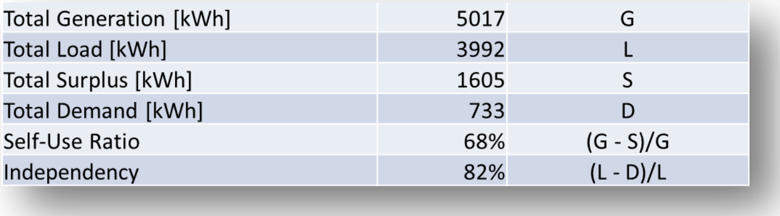
This sheet performs the main calculation routine of the simulation. One sheet just contains the global input variables and parameters for the calculation:



Name	Value	Symbol
PV Factor [kWp]	5	PV_{factor}
Load Factor 1000 kWh/a	4	L_{factor}
Battery Capacity [kWh]	10	C_{bat}
Battery Power Rating [kW]	5	P_{rated}
Battery Minimal SOC	20%	SOC_{min}
Battery Maximal SOC	80%	SOC_{max}
Battery Start SOC	20%	SOC_{start}
Generation Efficiency	83%	η_{pv}
Inverter Efficiency	97%	η_{inv}
Battery Efficiency	90%	η_{bat}
Battery Self-Discharge [%/15min]	0,002%	ρ_{bat}

Table 9: Input Parameters

The total values for selected data and the actual elapsed calculation time is also maintained here:



Total Generation [kWh]	5017	G
Total Load [kWh]	3992	L
Total Surplus [kWh]	1605	S
Total Demand [kWh]	733	D
Self-Use Ratio	68%	(G - S)/G
Independency	82%	(L - D)/L

Table 10: Output values

The PV generation values and the load profile data are mapped into two input spreadsheet (*Generation, Load*). Several sheets with a similar layout (96 by 365) are used to hold the calculated data as the simulation output. All output data sheets are accompanied by 3D surface charts. Those sheets are:

- Charge
- Surplus
- Demand
- Battery
- SOC
- Use
- Independence

Again a simple VBA script is used to calculate the output data:

```
' <copyright file="Calculation.xlsm" company="Dr. Peter Trimmel">
'     Copyright (c) 2011 Dr. Peter Trimmel. All rights reserved.
' </copyright>
' <module>CalculationModule</module>
' <summary>
'     The irradiation values (PV Generation.xlsm) and the load
'     profile data (Load Profile.xlsm) are used to calculate the
'     distribution of energy (generatio => load, surplus, battery).
'     Several scenarios are considered:
'         PV generation as from the PVGIS data (global irradiation)
'         Corrected generation values (clear sky and diffuse
'         irradiation data are used to acommodate intermittency).
'         For the peak load scenario a reduced load value is used.
' </summary>
'
' Global constants
Const ROW_OFFSET = 3
Const COL_OFFSET = 2
Const TIME_SPAN = 0.25
Const ROW_GLOBALS = 2

'
' Routine to calculate all simulation values (15 min period)
'
' Global parameters are used to drive the calculation.
' All output values are stored in associated sheets.
' Note that the generation sheet contains the total
' PV output for the period in kWh.
'
Sub CalculateAll()
    ' main variables
    Dim generation As Double
    Dim generationDiff As Double
    Dim generationClear As Double
    Dim eff_gen As Double
    Dim eff_inv As Double
    Dim eff_bat As Double
    Dim load As Double
    Dim load_peak As Double
    Dim load_c As Double
    Dim load_factor As Double
    Dim perc As Double
    Dim capacity As Double
    Dim rating As Double
    Dim soc_start As Double
    Dim soc_old As Double
    Dim soc_old_p As Double
    Dim soc_old_c As Double
    Dim soc_min As Double
    Dim soc_max As Double

    ' index variables
    Dim row As Integer
    Dim col As Integer
    Dim row_index As Integer
    Dim col_index As Integer

    ' data sheets
    Dim generationSheet As Worksheet
    Dim generationDiffSheet As Worksheet
    Dim generationClearSheet As Worksheet
    Dim loadSheet As Worksheet
    Dim chargeSheet As Worksheet
    Dim surplusSheet As Worksheet
    Dim demandSheet As Worksheet
    Dim batterySheet As Worksheet
    Dim socSheet As Worksheet
    ' PV peak sheets
    Dim chargepSheet As Worksheet
    Dim surpluspSheet As Worksheet
```

```
    Dim demandpSheet As Worksheet
    Dim batterypSheet As Worksheet
    Dim socpSheet As Worksheet
    Dim pSheet As Worksheet

    ' load peak corr. sheets
    Dim loadcSheet As Worksheet
    Dim chargecSheet As Worksheet
    Dim surpluscSheet As Worksheet
    Dim demandcSheet As Worksheet
    Dim batterycSheet As Worksheet
    Dim soccSheet As Worksheet

    ' calculated results
    Dim data As CData
    Dim datap As CData
    Dim datac As CData
    Dim dataDiff As CData
    Dim dataClear As CData

    ' setup timer
    Dim start As Single
    Dim finish As Single
    Dim elapsed As Single

    start = Timer

    Application.ScreenUpdating = False
    Application.DisplayStatusBar = True
    Application.Calculation = xlCalculationManual

    ' read global parameters
    load_factor = ThisWorkbook.Sheets("Data").Range("Load_Factor").Value
    capacity = ThisWorkbook.Sheets("Data").Range("Battery_Capacity").Value
    rating = ThisWorkbook.Sheets("Data").Range("Power_Rating").Value
    load_peak = ThisWorkbook.Sheets("Data").Range("Daily_Peak_Load").Value
    soc_min = ThisWorkbook.Sheets("Data").Range("SOC_Min").Value
    soc_max = ThisWorkbook.Sheets("Data").Range("SOC_Max").Value
    soc_start = ThisWorkbook.Sheets("Data").Range("SOC_Start").Value
    eff_gen = ThisWorkbook.Sheets("Data").Range("Generation_Efficiency").Value
    eff_inv = ThisWorkbook.Sheets("Data").Range("Inverter_Efficiency").Value
    eff_bat = ThisWorkbook.Sheets("Data").Range("Battery_Efficiency").Value
    sdr = ThisWorkbook.Sheets("Data").Range("Self_Discharge").Value / (4 * 24 * 30)

    ' get references to all sheets
    Set generationSheet = ThisWorkbook.Sheets("Generation")
    Set generationDiffSheet = ThisWorkbook.Sheets("Generation (d)")
    Set generationClearSheet = ThisWorkbook.Sheets("Generation (c)")
    Set loadSheet = ThisWorkbook.Sheets("Load")
    Set chargeSheet = ThisWorkbook.Sheets("Charge")
    Set surplusSheet = ThisWorkbook.Sheets("Surplus")
    Set demandSheet = ThisWorkbook.Sheets("Demand")
    Set batterySheet = ThisWorkbook.Sheets("Battery")
    Set socSheet = ThisWorkbook.Sheets("SOC")

    ' PV peak sheets
    Set chargepSheet = ThisWorkbook.Sheets("Charge (p)")
    Set surpluspSheet = ThisWorkbook.Sheets("Surplus (p)")
    Set demandpSheet = ThisWorkbook.Sheets("Demand (p)")
    Set batterypSheet = ThisWorkbook.Sheets("Battery (p)")
    Set socpSheet = ThisWorkbook.Sheets("SOC (p)")
    Set pSheet = ThisWorkbook.Sheets("p")

    ' Load peak corr. sheets
    Set loadcSheet = ThisWorkbook.Sheets("Load (c)")
    Set chargecSheet = ThisWorkbook.Sheets("Charge (c)")
    Set surpluscSheet = ThisWorkbook.Sheets("Surplus (c)")
    Set demandcSheet = ThisWorkbook.Sheets("Demand (c)")
    Set batterycSheet = ThisWorkbook.Sheets("Battery (c)")
    Set soccSheet = ThisWorkbook.Sheets("SOC (c)")

    soc_old = soc_start
    soc_old_p = soc_start
    soc_old_c = soc_start
    perc = 1

    For col = 1 To 365
```

```
        For row = 1 To 96
            Application.StatusBar = "SOC[" & row & "," & col & "]"

            row_index = row + ROW_OFFSET
            col_index = col + COL_OFFSET

            ' get generation and load data
            generation = generationSheet.Cells(row_index, col_index).Value
            generationDiff = generationDiffSheet.Cells(row_index, col_index).Value
            generationClear = generationClearSheet.Cells(row_index, col_index).Value
            load = loadSheet.Cells(row_index, col_index).Value

            ' apply losses and efficiencies
            generation = generation * eff_gen
            generationDiff = generationDiff * eff_gen
            generationClear = generationClear * eff_gen

            ' load requirements are increased due inverter losses
            load = load / eff_inv

            ' correct the load based on the daily peak value
            load_c = load * (load_factor - load_peak * 0.365) / load_factor

            soc_old = soc_old * (1 - sdr)
            soc_old_p = soc_old_p * (1 - sdr)
            soc_old_c = soc_old_c * (1 - sdr)

            ' calculate standard simulation values as a reference
            Set data = CalculateSOC(generation, load, soc_old, soc_min, _
                                    soc_max, capacity, rating)

            ' if clear sky, global, and diffuse generation values are valid apply
peak correction
            If (generationClear > generation) And (generation > generationDiff) Then

                ' calculate peak percentage
                perc = (generation - generationDiff) / _
                       (generationClear - generationDiff)

                Set datap = New CData

                ' generate peak area data (perc * 15 min)
                Set dataClear = CalculateSOC(perc * generationClear, _
                                             perc * load, soc_old_p, soc_min, _
                                             soc_max, capacity, rating)

                ' generate diffuse area data (1 - perc) * 15 min
                Set dataDiff = CalculateSOC((1 - perc) * generationDiff, _
                                            (1 - perc) * load, dataClear.soc, _
                                            soc_min, soc_max, capacity, rating)

                ' calculate final simulation values
                datap.charge = dataClear.charge + dataDiff.charge
                datap.surplus = dataClear.surplus + dataDiff.surplus
                datap.demand = dataClear.demand + dataDiff.demand
                datap.soc = dataDiff.soc

                ' calculate all simulation values corrected for daily peak loads
                Set datac = New CData

                ' generate peak area data (perc * 15 min)
                Set dataClear = CalculateSOC(perc * generationClear, _
                                             perc * load_c, soc_old_c, soc_min, _
                                             soc_max, capacity, rating)

                ' generate diffuse area data (1 - perc) * 15 min
                Set dataDiff = CalculateSOC((1 - perc) * generationDiff, _
                                            (1 - perc) * load_c, dataClear.soc, _
                                            soc_min, soc_max, capacity, rating)

                ' calculate final simulation values
                datac.charge = dataClear.charge + dataDiff.charge
                datac.surplus = dataClear.surplus + dataDiff.surplus
                datac.demand = dataClear.demand + dataDiff.demand

                datac.soc = dataDiff.soc
```

```
            Else

                ' calculate new simulation values
                Set datap = CalculateSOC(generation, load, soc_old_p, soc_min, _
                                         soc_max, capacity, rating)

                ' calculate corrected simulation values
                Set datac = CalculateSOC(generation, load_c, soc_old_c, soc_min, _
                                         soc_max, capacity, rating)

            End If

            ' demand goes directly from the grid to the load
            data.demand = data.demand * eff_inv
            datap.demand = datap.demand * eff_inv
            datac.demand = datac.demand * eff_inv

            ' store calculated data in worksheets
            chargeSheet.Cells(row_index, col_index).Value = data.charge
            surplusSheet.Cells(row_index, col_index).Value = data.surplus
            demandSheet.Cells(row_index, col_index).Value = data.demand
            batterySheet.Cells(row_index, col_index).Value = data.soc * capacity
            socSheet.Cells(row_index, col_index).Value = data.soc

            ' store calculated data in (p) worksheets
            chargepSheet.Cells(row_index, col_index).Value = datap.charge
            surpluspSheet.Cells(row_index, col_index).Value = datap.surplus
            demandpSheet.Cells(row_index, col_index).Value = datap.demand
            batterypSheet.Cells(row_index, col_index).Value = datap.soc * capacity
            socpSheet.Cells(row_index, col_index).Value = datap.soc

            ' store calculated data in (c) worksheets
            loadcSheet.Cells(row_index, col_index).Value = load_c * eff_inv
            chargecSheet.Cells(row_index, col_index).Value = datac.charge
            surpluscSheet.Cells(row_index, col_index).Value = datac.surplus
            demandcSheet.Cells(row_index, col_index).Value = datac.demand
            batterycSheet.Cells(row_index, col_index).Value = datac.soc * capacity
            soccSheet.Cells(row_index, col_index).Value = datac.soc

            ' update battery SOC
            soc_old = data.soc
            soc_old_p = datap.soc
            soc_old_c = datac.soc
        Next
    Next

    Application.Calculation = xlCalculationAutomatic
    Application.ScreenUpdating = True
    Application.StatusBar = False
    Application.Calculate

    finish = Timer
    elapsed = Format(finish - start, "Fixed")
    ThisWorkbook.Sheets("Data").Range("Elapsed_Time").Value = elapsed

End Sub
'
' Routine to calculate the SOC value (after period)
'
' Parameter
'     generation - Generation PV in kWh (in period)
'     load       - Load in kWh (in period)
'     soc_old    - SOC of battery (before period)
'     soc_min    - Minimal SOC of battery
'     soc_max    - Maximal SOC of battery
'     capacity   - Capacity of battery
'     rating     - Capacity of battery
'
' Return Value
'     data       - Data set with new values
'
Function CalculateSOC(ByVal generation As Double, _
                      ByVal load As Double, _
                      ByVal soc_old As Double, _
                      ByVal soc_min As Double, _
                      ByVal soc_max As Double, _
                      ByVal capacity As Double, _
```

```
                      ByVal rating As Double) As CData
    Dim use As Double
    Dim charge As Double
    Dim surplus As Double
    Dim demand As Double
    Dim soc As Double

    soc = 0
    charge = 0
    demand = 0
    surplus = 0

    If (capacity > 0) Then

        charge = generation - load

        If (rating > 0) And (Abs(charge) / TIME_SPAN > rating) Then

            charge = Sgn(charge) * rating * TIME_SPAN

            If (charge > 0) Then
                surplus = generation - (load + charge)
            Else
                demand = load - (generation - charge)
            End If

        End If

        If (generation > load) Then ' charge > 0

            If (soc_old < soc_max) Then

                If charge > (soc_max - soc_old) * capacity Then

                    charge = (soc_max - soc_old) * capacity
                    surplus = generation - (load + charge)

                End If

                Else ' (soc_old > soc_max)

                    charge = 0
                    surplus = generation - load

                End If

            End If

        Else ' generation < load, charge < 0

            If (soc_old > soc_min) Then

                If charge < (soc_min - soc_old) * capacity Then

                    charge = (soc_min - soc_old) * capacity
                    demand = load - (generation - charge)

                End If

            Else ' soc_old < soc_min

                charge = 0
                demand = load - generation

            End If

        End If

        soc = soc_old + charge / capacity

    Else ' capacity = 0

        If (generation > load) Then

            surplus = generation - load

        Else ' generation < load
```

```
            demand = load - generation

        End If

    End If

    Set CalculateSOC = New CData

    CalculateSOC.charge = charge
    CalculateSOC.demand = demand
    CalculateSOC.surplus = surplus
    CalculateSOC.soc = soc

End Function
```

A custom class is used to store results:

```
' <copyright file="Calculation.xlsm" company="Dr. Peter Trimmel">
'     Copyright (c) 2011 Dr. Peter Trimmel. All rights reserved.
' </copyright>
' <module>CData</module>
' <summary>
'     This is a class module which defines a custom class to
'     hold the calculation data set.
' </summary>
'
Private pCharge As Double           ' Energy transferred to battery (kWh)
Private pSurplus As Double          ' Energy surplus in period (kWh)
Private pDemand As Double           ' Energy demand in period (kWh)
Private pSOC As Double              ' SOC of battery (after period)
Private pSelf As Double             ' Energy Self-Use in period (%)

'
' Charge property - Energy transferred to and from battery (kWh)
'
Public Property Get charge() As Double
    charge = pCharge
End Property
Public Property Let charge(Value As Double)
    pCharge = Value
End Property

'
' Surplus property - Energy surplus in period (kWh)
'
Public Property Get surplus() As Double
    surplus = pSurplus
End Property
Public Property Let surplus(Value As Double)
    pSurplus = Value
End Property

'
' Demand property - Energy demand in period (kWh)
'
Public Property Get demand() As Double
    demand = pDemand
End Property
Public Property Let demand(Value As Double)
    pDemand = Value
End Property

'
' SOC property - SOC of battery (after period)
'
Public Property Get soc() As Double
    soc = pSOC
End Property
Public Property Let soc(Value As Double)
    pSOC = Value
End Property
```

Note that special handling of zero battery capacity and / or battery rating has been implemented.

8.3.6 Daily View.xslm

Finally this macro enable spreadsheet allows quick reporting for selected daily result values.

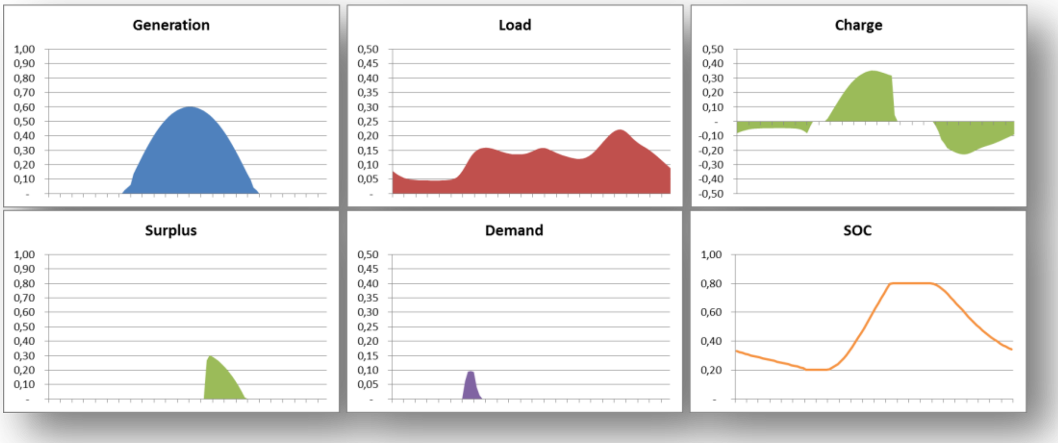
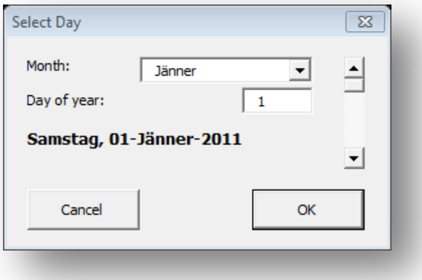


Figure 111: Daily Report Charts

A dialog box allows selecting the day of the year used for reporting:



Month: Jänner
Day of year: 1
Samstag, 01-Jänner-2011

Figure 112: Day Selection Dialog

The following VBA code is used to generate the charts (see Annexes 7.1 Simulation Results):

```
' <copyright file="Daily View.xlsm" company="Dr. Peter Trimmel">
'     Copyright (c) 2011 Dr. Peter Trimmel. All rights reserved.
' </copyright>
' <module>SelectDayForm</module>
' <summary>
```

```
'     This is a form which allows to select a day of the year
'     for further report generation.
' </summary>
'
Const CURRENT_YEAR = 2011
Const COL_GLOBALS = 2
Const ROW_DOY = 1
Const ROW_DATE = 2
Const ROW_OFFSET = 4
Const COL_OFFSET = 4
Const COL_GENERATION = 3
Const COL_LOAD = 4
Const COL_CHARGE = 5
Const COL_SURPLUS = 6
Const COL_DEMAND = 7
Const COL_BATTERY = 8
Const COL_SOC = 9
Const COL_GENERATION_D = 10
Const COL_GENERATION_C = 11
Const COL_CHARGE_P = 12
Const COL_SURPLUS_P = 13
Const COL_DEMAND_P = 14
Const COL_BATTERY_P = 15
Const COL_SOC_P = 16
Const COL_LOAD_C = 17
Const COL_CHARGE_C = 18
Const COL_SURPLUS_C = 19
Const COL_DEMAND_C = 20
Const COL_BATTERY_C = 21
Const COL_SOC_C = 21

Dim currentDate As Date

' If the cancel button is clicked the form closes.
Private Sub CancelButton_Click()
    End
End Sub

' If the OK button is clicked the daily data are retrieved.
Private Sub OkButton_Click()
    ' main variables
    Dim row As Integer
    Dim col As Integer
    Dim addr As String

    ' setup timer
    Dim start As Single
    Dim finish As Single
    Dim elapsed As Single

    start = Timer

    Application.ScreenUpdating = False
    Application.DisplayStatusBar = True
    Application.Calculation = xlCalculationManual

    col = ScrollBar.value - 1
    ThisWorkbook.Sheets("Data").Cells(ROW_DOY, COL_GLOBALS).value = ScrollBar.value
    ThisWorkbook.Sheets("Data").Cells(ROW_DATE, COL_GLOBALS).value = currentDate

    For row = 0 To 95
        addr = ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, col + _
                                                 COL_OFFSET).Address
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_GENERATION).Formula =
"=[Calculation.xlsm]Generation!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_LOAD).Formula =
"=[Calculation.xlsm]Load!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_CHARGE).Formula =
"=[Calculation.xlsm]Charge!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_SURPLUS).Formula =
"=[Calculation.xlsm]Surplus!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_DEMAND).Formula =
"=[Calculation.xlsm]Demand!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_BATTERY).Formula =
"=[Calculation.xlsm]Battery!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_SOC).Formula =
"=[Calculation.xlsm]SOC!" & addr
```

```
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_GENERATION_D).Formula
= "='[Calculation.xlsm]Generation (d)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_GENERATION_C).Formula
= "='[Calculation.xlsm]Generation (c)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_CHARGE_P).Formula =
"='[Calculation.xlsm]Charge (p)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_SURPLUS_P).Formula =
"='[Calculation.xlsm]Surplus (p)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_DEMAND_P).Formula =
"='[Calculation.xlsm]Demand (p)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_BATTERY_P).Formula =
"='[Calculation.xlsm]Battery (p)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_SOC_P).Formula =
"='[Calculation.xlsm]SOC (p)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_LOAD_C).Formula =
"='[Calculation.xlsm]Load (c)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_CHARGE_C).Formula =
"='[Calculation.xlsm]Charge (c)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_SURPLUS_C).Formula =
"='[Calculation.xlsm]Surplus (c)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_DEMAND_C).Formula =
"='[Calculation.xlsm]Demand (c)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_BATTERY_C).Formula =
"='[Calculation.xlsm]Battery (c)'!" & addr
        ThisWorkbook.Sheets("Data").Cells(row + ROW_OFFSET, COL_SOC_C).Formula =
"='[Calculation.xlsm]SOC (c)'!" & addr

    Next

    Application.Calculation = xlCalculationAutomatic
    Application.ScreenUpdating = True
    Application.StatusBar = False
    Application.Calculate

    finish = Timer
    elapsed = Format(finish - start, "Fixed")
    ThisWorkbook.Sheets("Data").Range("Elapsed_Time").value = elapsed

    End
End Sub

' The date is updated when the scrollbar changes.
Private Sub ScrollBar_Change()
    SetDate ScrollBar.value
End Sub

' The date is updated when a new month is selected.
Private Sub MonthBox_Change()
    Dim d As Integer
    Dim m As Integer
    Dim n As Integer

    d = Day(currentDate)
    m = MonthBox.ListIndex + 1
    n = DaysInMonth(m)

    If (d > n) Then
        d = n
    End If

    currentDate = DateSerial(CURRENT_YEAR, m, d)
    ScrollBar.value = DaysOfYear(currentDate)
End Sub

' The form is initialized.
Private Sub UserForm_Initialize()
    MonthBox.AddItem MonthName(1)
    MonthBox.AddItem MonthName(2)
    MonthBox.AddItem MonthName(3)
    MonthBox.AddItem MonthName(4)
    MonthBox.AddItem MonthName(5)
    MonthBox.AddItem MonthName(6)
    MonthBox.AddItem MonthName(7)
    MonthBox.AddItem MonthName(8)
    MonthBox.AddItem MonthName(9)
    MonthBox.AddItem MonthName(10)
    MonthBox.AddItem MonthName(11)
```

```
    MonthBox.AddItem MonthName(12)

    SetDate ScrollBar.value
End Sub

' The date related fields are updated.
Sub SetDate(ByVal value As Integer)
    DayTextBox.Text = value
    currentDate = DateAdd("d", value - 1, DateSerial(CURRENT_YEAR, 1, 1))
    MonthBox.value = MonthName(Month(currentDate))
    DateLabel = Format(currentDate, "dddd, dd-mmmm-yyyy")
End Sub

' Helper routine to get the days in a month.
Function DaysInMonth(ByVal value As Integer) As Integer
    DaysInMonth = DateSerial(CURRENT_YEAR, value + 1, 1) - _
                  DateSerial(CURRENT_YEAR, value, 1)
End Function

' Helper function to get the day of the year.
Function DaysOfYear(ByVal value As Date) As Integer
    DaysOfYear = DateSerial(CURRENT_YEAR, Month(value), Day(value)) - _
                 DateSerial(CURRENT_YEAR, 1, 1) + 1
End Function
```

And the macro to be called is defined too:

```
' <copyright file="Daily View.xlsm" company="Dr. Peter Trimmel">
'     Copyright (c) 2011 Dr. Peter Trimmel. All rights reserved.
' </copyright>
' <module>SelectDayForm</module>
' <summary>Macro to show the select day dialog.</summary>
'
Public Sub SelectDay()
    Dim form As SelectDayForm

    Set form = New SelectDayForm
    form.Show
End Sub
```