Stand-Alone Energy Supply of Households

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Abstract

Recently there has been growing interest in energy saving and in the de-centralised production of energy especially electricity from renewable sources. This project tries to highlight the differences and advantages and disadvantages of grid-connected photovoltaic systems and stand alone systems. A critical role in this system plays the interaction between the solar cells, the inverter and the charge controller and battery. In addition the influence of the consumer behavior characterized by load profiles and also different types of devices on the design of system-components are investigated. For good performance the operation of a demand side management system is required.

1. Introduction

Austria and other countries in Europe, record an annual increase in energy consumption, which raises the problem of national energy supply and uncertainties because of an growing dependency on imports. Since the nuclear catastrophe in Fukushima and the subsequent dispute over nuclear phase-out in Germany and other countries, energy has become in the focus of the community within Europe.

Because of the greenhouse effect, renewable energy sources will have an increasingly important role in the future. The biggest problem with the electricity generation from renewable energy sources, especially from wind and sun, is the fluctuating supply trend. This means that, a constant production of electricity is not possible with solar- or wind-power. Therefore, either large storage systems are required or the power consumption must be adapted to the production of electricity. Depending on the workload, the costs for electricity production over the day is no longer constant but varies. In addition, in the next few years, the conventional current electricity meters will be changed to so-called smart meters. Smart meters are connected to the energy provider so instantaneous power consumption can be determined.

In order to adapt the energy supply to the future requirements, the transmission network must be expanded. The increased assignment of fluctuating (volatile) energy sources like renewable energy and new power distribution systems, like smart grids and smart meters, will make electrical power more expensive in the future.

On the other hand, photovoltaic systems have become more affordable and economically interesting. In the last years photovoltaic systems became cheaper and cheaper whereas the efficiency increased.

By now, solar energy is on its way to become a standard part of installation technology. According to the study “SET For 2020”accomplished by the EPIA (European Photovoltaic Industry Association), photovoltaic (PV) may reach a 12 percent share in the European electricity supply by 2020 (so far – less than 1 percent). In order to achieve this goal, governments and regulators have to arrange for better conditions. In parts of southern Europe the generation of electricity out of photovoltaic will reach grid parity in the next few years[1]. This is an indispensable prerequisite to exist in future without subsidies and subventions. The study emphasizes furthermore that, as photovoltaic is the fastest growing renewable energy technology, a quicker decline of system costs compared to other renewable energy sources is expected.

The PV-market in Austria follows the amount and conditions of subsidies given by the government. If it would be possible to produce electricity with PV at lower costs than those arising from grid supply this situation would change dramatically. However, the optimum use of solar energy can only be obtained if the individual, local conditions are considered in the plant design. It is no longer sufficient just to install high-quality components. The crucial point is that these components need to be integrated carefully and the plant size must be adapted to the given circumstances.

In the planning of stand-alone systems (like Illustrated in Fig. 1- electrical components are outlined with dashed line) various approaches and optimization steps are required:

- Modeling of the consumer load profiles and other boundary conditions
- Minimization of the total consumption (efficient devices, awareness of the user)
- Low acquisition costs of the energy generator and storage
- Smoothing of the consumption curve – the consumption profile as steady as possible (no high peaks) →Demand Side Management (DSM)
- Accurate sizing and coordination of all components to each other
- Combined Heat and Power (CHP) for good fuel utilization
- User possibly suffers restrictions (e.g. limitation of power)

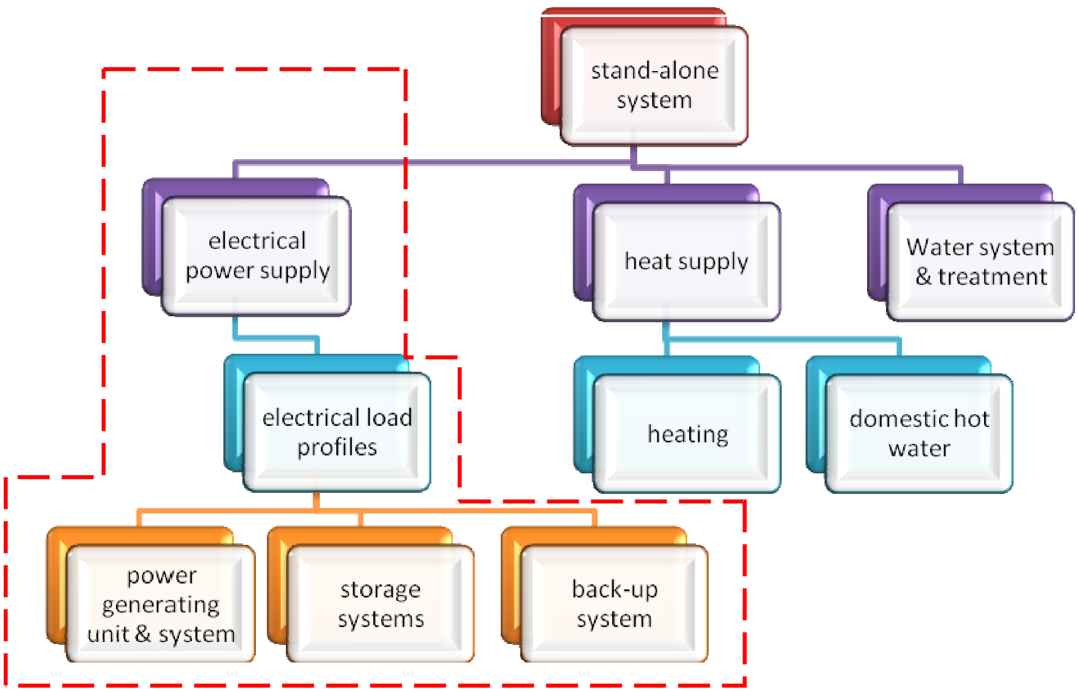

Fig. 1: Components of an energy concept for a stand-alone system

2. Model household

The considered model house is designed for three persons with 128 m² ground space (divided into two floors) and a maximal energy index (heating demand) of 30 kWh/m²a.

[1] source: EPIA – European Photovoltaic Industry Association (2009)

The standard load profile H0[2] is valid for all private households, and households with low commercial needs without installed storage heating or heat pump, with energy consumption smaller than 8000 kWh. The figure below shows standard load profiles for different days and seasons.

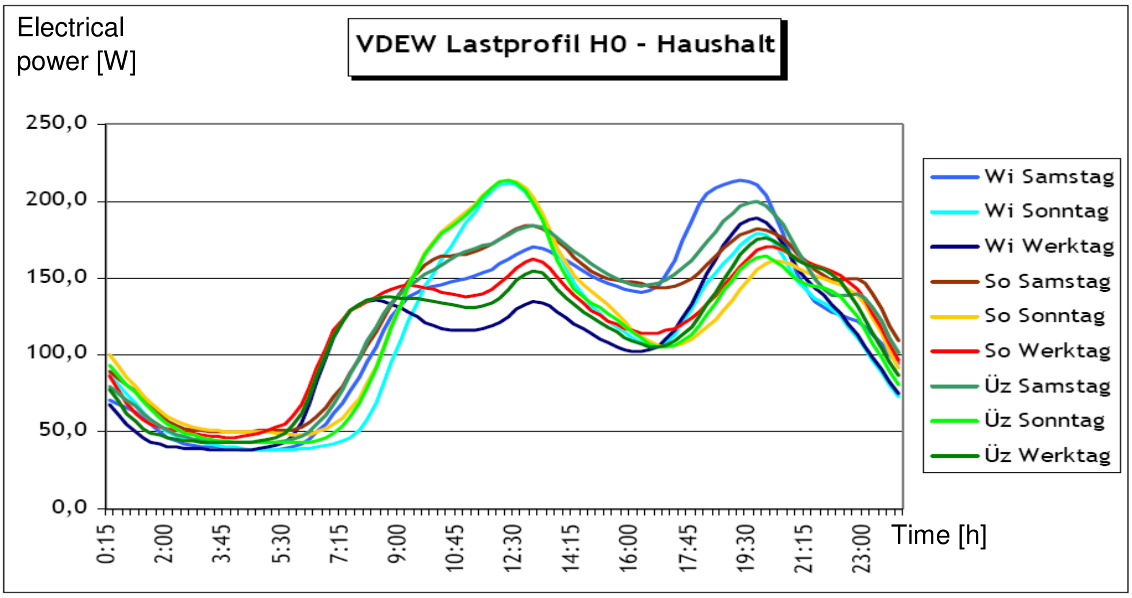

Fig. 2: Standard load profile H0 during one day. Average values of consumption over 15 minutes are shown.

Over the year, monthly consumed energy is lower in summer than in winter like shown in Fig. 3. The reduction is in the range of 25% and has to be taken into account during planning.

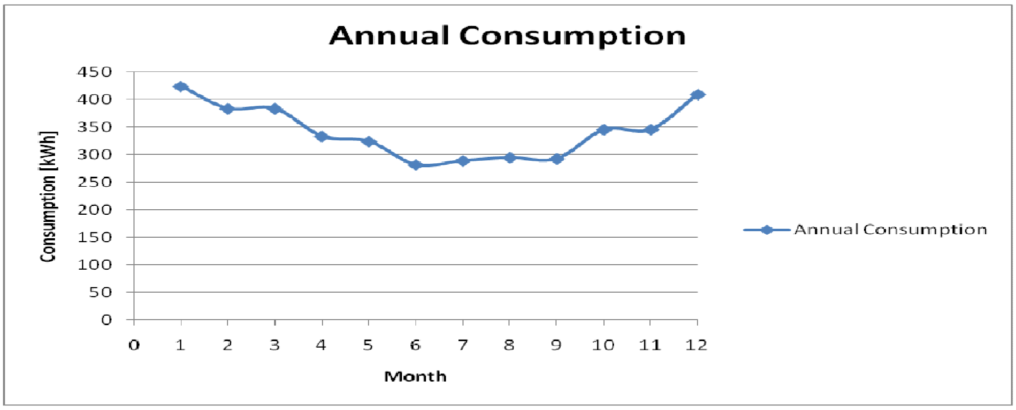

Fig. 3: Monthly energy consumption according to H0 load profile during one year.

In general simulation programs and energy providers are dealing with average consumer values in their calculations. As long as daily trends are observed this may be sufficient but if dimensioning of inverters and batteries is made more precise data is required. Therefore monitoring of a private household was installed to get information on power requirements and electricity consumption and minute-base. The typical graph of a daily consumption curve is shown in Fig. 4.

[2] VDEW-Verband der Elektrizitätswirtschaft- standard profiles

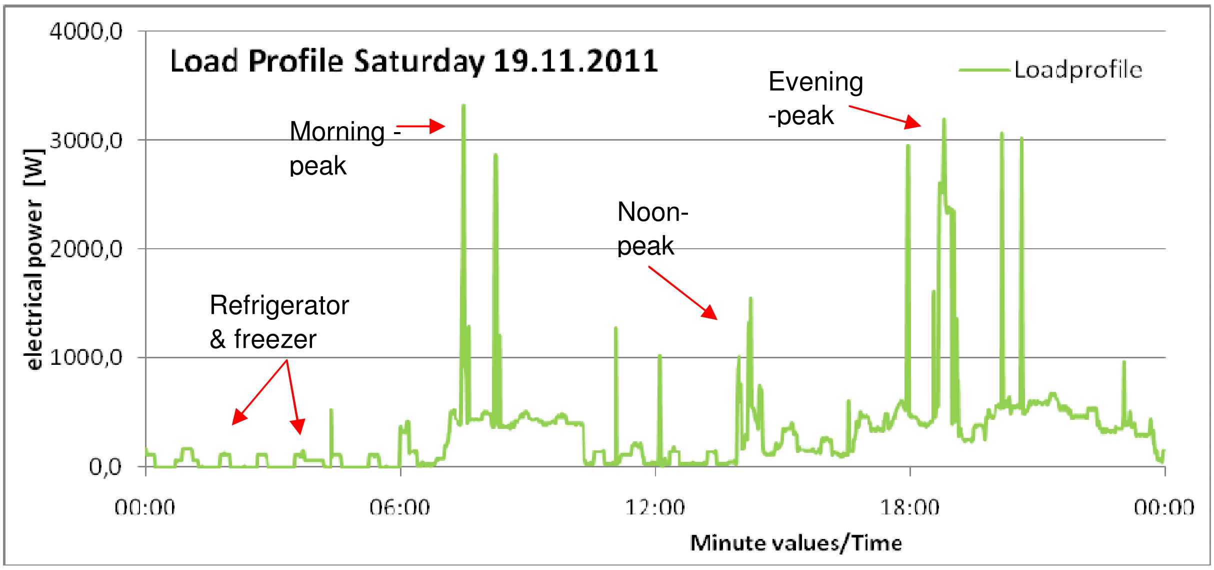

Fig. 4: Measured profile in one minute power consumption values of a private household

According to the graph the electrical load can be divided into a base-load (low fluctuating, max 700W in the shown example in Fig. 4) and a power load reaching much higher power. In the base load all small devices like radio, television, computer, lights, heating engineering and so on are included. The freezer and refrigerator are counted to the base load, because the turn-on times are distributed over the whole day. The consumer information according to a private model household is listed in Table 1: Consumer information of a private model household

Devices	activation	Power [W]
Electric cooker, fume cupboard	Cooking daily at about 2 pm	3000
Kettle	about ten times a day	2500
Toaster	every day, in the morning	750
Washing machine	every day, more often on weekends	2200
Laundry dryer	every day in winter, more often on weekends	2500
Dish washer	every day	1700
Hairdryer	every day	1000
Lights (11W energy saving lamps)	about 15 lights switched on when darkness	a´11
Vacuum cleaner	twice a week	500
Iron	about twice a week	1600
Various radiators	($T_A \leq 5$℃) irregularly 1-2 hours per day	a´1000
HIFI, Computer	about 5 hours a day	150
Pellet stove	about 5 hours a day in winter	100
Refrigerator	automatically controlled	90
Freezer	automatically controlled	Ca. 140

Table 1: Consumer information of a private model household

The minute-values measured in the monitoring system (like shown in Fig. 4: Measured profile in one minute power consumption values of a private household were classified according to the height of the electrical power. The blue column shows the share of the different electrical power classes on the total energy consumption of the load profile from 19 November to 04 December. The red column shows the share of the different electrical power classes on the total energy demand of the load profile from 21 November to 27 November. If one compares figures from the first five classes of both columns, it can be seen that the base load percentage is nearly the same. The base load percentage is approximately 75%. The peak load percentage with a very high level of power consumption is approximately 25%.

	Load profile 19.11-04.12	Load profile 21.11.-27.11.	Electrical power [W]
Class 1 [%]	38,68	46,87	<150
Class 2 [%]	11,54	8,01	150-300
Class 3 [%]	9,73	6,64	300-450
Class 4 [%]	8,77	5,73	450-600
Class 5 [%]	9,00	8,21	600-750
Class 6 [%]	6,90	6,66	750-1250
Class 7 [%]	2,02	2,10	1250-1750
Class 8 [%]	4,60	6,54	1750-2250
Class 9 [%]	4,62	5,84	2250-2750
Class 10 [%]	4,14	3,40	>2750
SUMME [%]	100,00	100,00	

Base load ~ 75% (Classes 1–5)

Peak load ~ 25% (Classes 6–9)

Table 2: Classification of the power profile

This classification is needed to evaluate the maximum possible degree of supply of the inverter installed. An inverter that provides 750W electrical power can supply a maximum of 75% of the demand profile on which the data in Table 2 is based on regardless of the installed PV-power.

3. Demand side management (DSM)

Demand side management is one of the most important components of a photovoltaic-based stand-alone system. The main tasks of a demand side management as also illustrated in Fig. 5 are:

- Reduce the peaks and the overall energy demand
- Reduce the power fluctuation caused by consumer behavior
- Peak shaving
- Shift the peak loads to low load periods where the battery is fully charged
- Optimize the operating times from the photovoltaic system
- Reduce the operating times from the back-up system

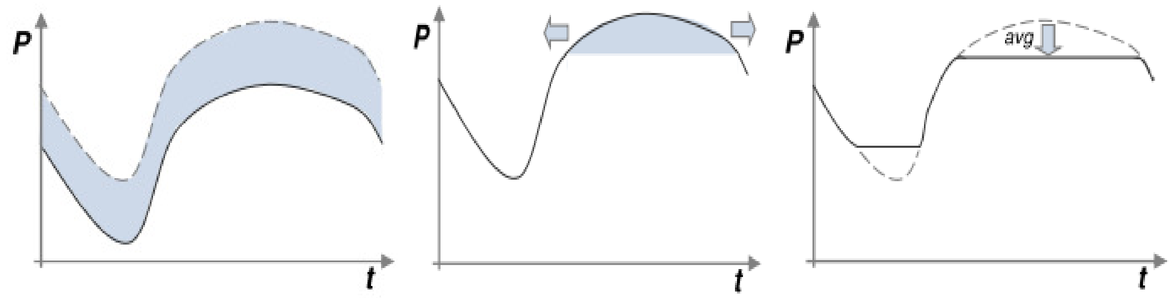

Fig. 5: Effects on average power, load shifting, and peak reduction by a demand side management

To have a basis to work with, it is necessary to define a model household with its electric devices and the energy demand. The model and the assumed profiles are described in the previous chapter. The model household includes three persons with an electricity demand of 4000kWh/a, this is about 11 kWh per day in average.

The aim of the DSM is to manage the energy transfer between generator CHP, AKKU (battery), PV in Fig. 8) and consumer (upper boxes in in Fig. 8). The power demand profile should overlap as much as possible with the profile of the generated energy of the sources.

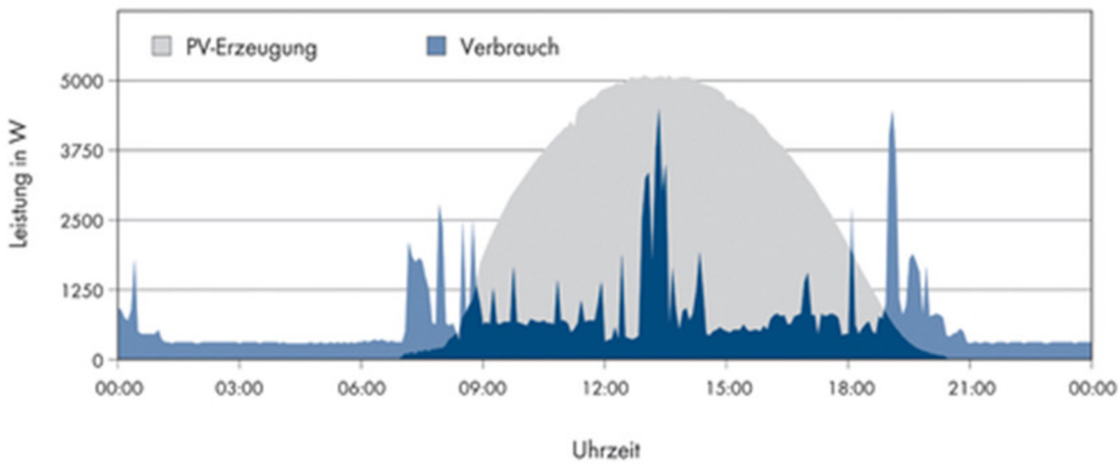

Fig. 6: Illustration the fraction of direct consumed energy due to overlap of PV-profile and consumer profile

In Fig. 6 the overlap of generation and consummation is shown. Without additional measures the overlap is dependent on the size of the PV-panel and the consummation. A producer gives typical numbers (in Fig. 7) for 3-4 person households and PV peak power of 5kWh: 30%-40% of the produced electricity can be direct consumed. This value can drop to 10% or less in case of smaller households.

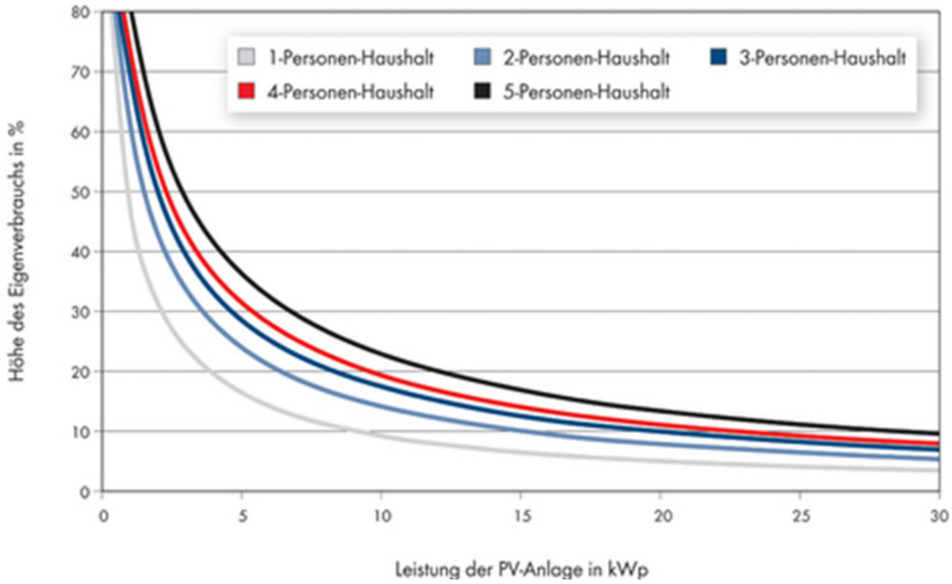

Fig. 7: Amount of electric energy directly consumed without additional measures[3]

The ability of the DSM to adapt to the generation profile of the PV generator is of key importance for the whole system. Only if a certain amount of energy produced by the PV generator is directly used idea of the technical principle is working. This fraction of directly consumed electricity is depending on the size of the installed PV panels, the typical consumer behavior and the ability of the DSM to adapt to the daily conditions of energy production and consumption.

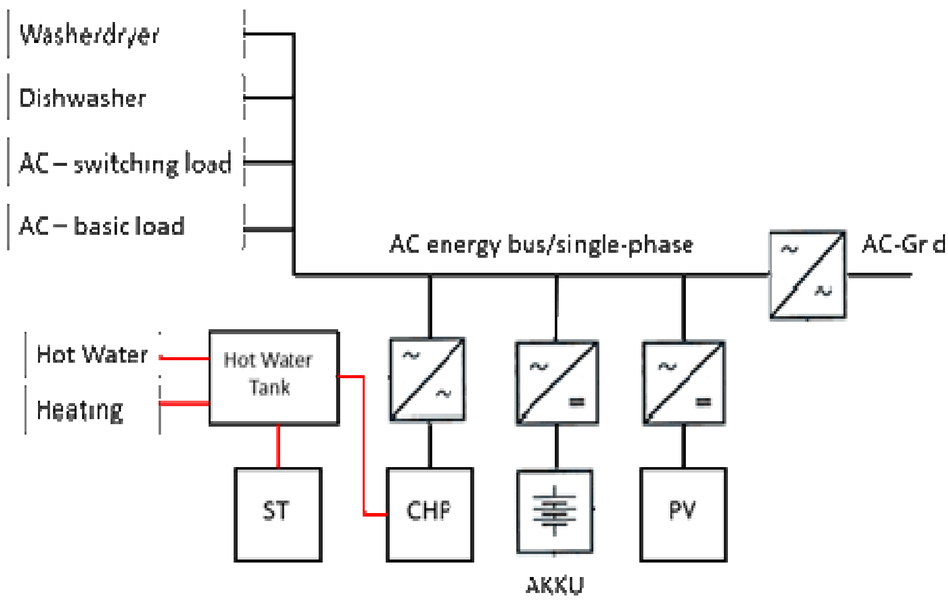

Fig. 8: Principle of the energy supply stand-alone system with AC-grid backup

Demonstration system

To demonstrate Demand Side Management a simplified concept was realized. The concept consists of a energy input simulating the photovoltaic generator, a battery, a charging regulator, and a standalone inverter. In Fig. 9 the concept is shown.

[3] Source: www.sma.de

The thermal energy is not considered at all. The loads are divided into three areas, the switchable and time-shift able loads (like the dishwasher, the washing machine, laundry dryer, tap water heater), the general loads (cooker and devices connected to the plugs) and base load that is installed (e.g.: lights).

The different areas and devices can be switched alternatively to the public grid or to the island home grid. The load control is realized by a Siemens PLC. Therefore it is necessary to measure the power consumption in each area and the converter power. Additionally the PLC gets some status information from the battery, the converter, the solar radiation and the operating mode. To switch the devices between the home grid and the public grid toggle switches are used. To switch single devices connected to plugs like dishwasher and the washing machine FS20 radio outlets are used.

The operating mode can be selected between automatic, manual and off. In the automatic mode the power demand is controlled by the PLC. If the power consumption in the home grid is too high some areas or devices are toggled from the home grid to the public grid. In addition the washers and the dryer are turned on one after the other, depending on the time of the day and the actual power generation of the PV panel.

In the manual mode some devices like cooker, washing machine and dishwasher are permanently connected to the public grid. This mode is recommended for permanent high demand, or repeated use of washers for example on Saturday or Sunday.

If the operating mode is in the off position all devices and areas are connected to the public grid. This is recommended for maintenance, and service. How the management system works in detail is described in the software description.

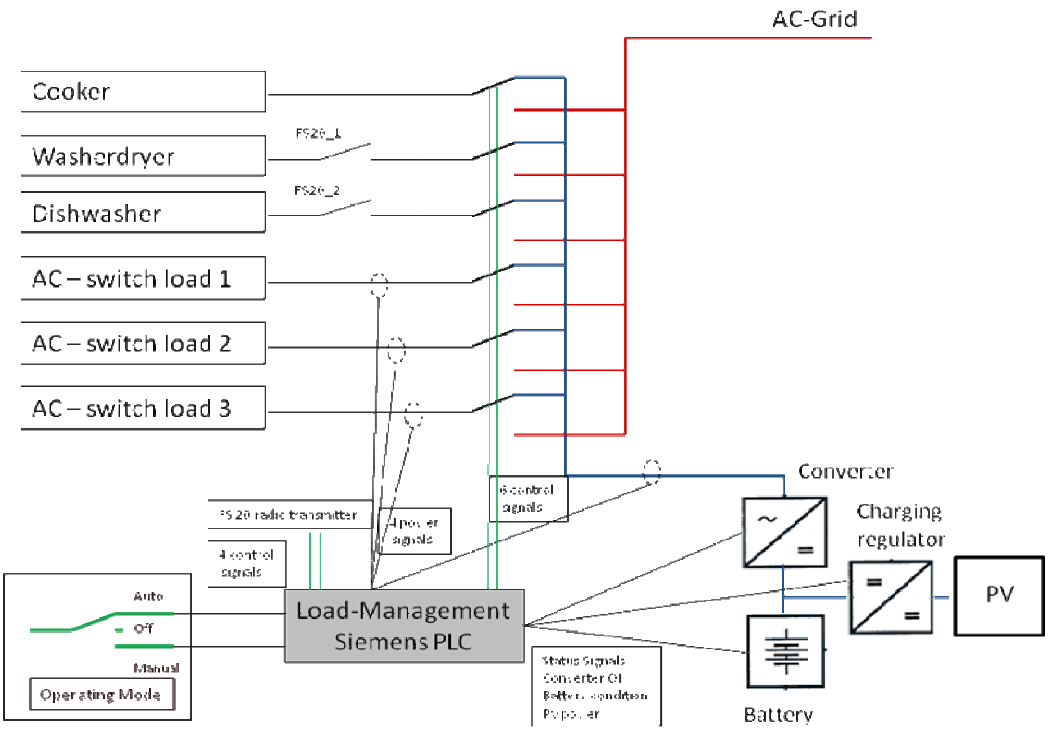

Fig. 9: Demonstration concept

The aim of this concept is to use the complete energy generated by the photovoltaic (PV) in the house. There is no need to feed PV energy into the public grid. The generator is isolated from the grid at any time, therefore not regulations and limitations from the side of the energy provider have to be taken into account.

With the use of smart DSM concepts it should be possible to reach much higher fractions of directly consumed energy than without. Instead of 30% at least 50-60% of the produced PV electricity should be directly consumed even without use of additional storage in batteries.

4. Energy storage

Island systems like, for caravans, boats, emergency telephones, or telecommunications applications already used widely. It has been has shown that private consumers can also rely on such systems. In the Netherlands for example an electricity-independent house is operated which is supplied by PV 28 panels and 48 batteries. The PV generator produces 4200 kWh a year and the batteries have a storage capacity of 300 kWh. With fully charged batteries, the house can be supplied with electricity for one month.

In general the number of existing stand-alone systems for family homes is very low. The majority of the installed PV generators are grid-connected photovoltaic systems. Island systems are often used in southern latitudes, especially in rural areas without grid-connection. In central Europe stand-alone systems are often used for mountain huts. Most of them are operated in summer solely.

The implementation of a stand-alone system is technically not a problem. In remote areas without grid connection they are also usually cheaper to operate than the construction of long supply lines. Nevertheless apparatus (inverters, chargers, etc) and batteries are rather expensive and systems have to be designed carefully.

One of the most important facts is to ensure proper battery management of the used batteries (mostly lead batteries with gelled electrolyte) to ensure lifetime and to avoid additional costs due to battery failure.

Several sophisticated charge controller or bidirectional inverter/charger are available. They provide good charging behavior for long battery lifetime. It has to be taken into account that the charger cannot finish charging cycles only with PV supply, since charging cycles consist of several time consuming phases. A typical time demand of the first phase (Bulk hours in Fig. 10) are 2-4 hours but complete cycle inclusive absorption phase needs about 12 hours. To ensure compete load cycles grid support is necessary during the nighttime.

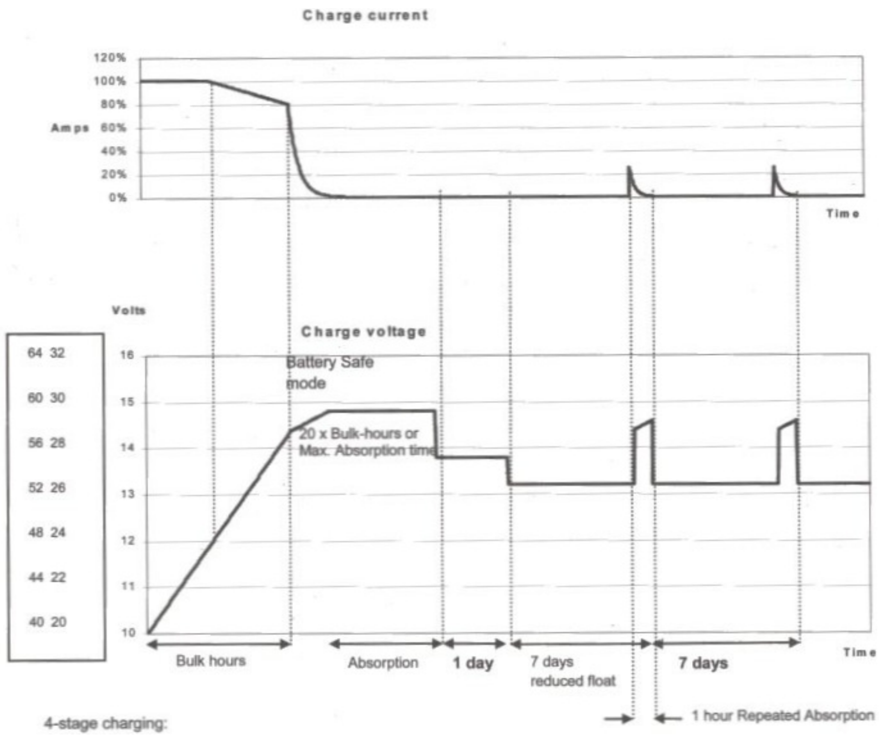

Fig. 10: Typical battery charging cycle[4]

[4] Source: www.victronenergy.com

5. Backup-supply, stand alone supply, and economic aspects

Until now direct consummation of electricity, efficient devices and demand side management (DSM) were part of the project. All these concepts were made under the general requirement to be competitive to grid supply as much as possible.

For true stand-alone supply of a household several additional aspects have to be taken into account:

- Energy supply for cooking
- Heat supply for tap water and heating
- Off grid electricity generation in winter

For the cooker in general three opportunities are possible: gas cooker, electric cooker, combined gas and electric cooker.

A combined gas and electric cooker has for example two gas hot plates and two electric hot plates and an electric oven. Such devices are available in the market. With such a cooker it would be possible to reduce the connected electricity load and to reach high adaption to daily conditions with rather simple measures: preferably use of gas in case of low solar radiation and preferably use of electric cooker in case of high radiation.

Off grid generation of electricity can be done by CHP generators in principle. Combustion machines using vegetarian oil are available and reach as high reliability and lifetime than diesel engines. Nevertheless operation of such systems is service intensive and cost arises therefore. Demonstration systems for supply of mountain huts with heat and electricity are already built[5].

Economic aspects

In order to highlight economic aspects some simulation and consideration of investment costs were performed.

The simulation of operation of different system designs has shown that there are some opportunities for optimization of a stand-alone system. Raising the depth of discharge (DoD) has a special effect on the cycles and therefore the lifetime of the batteries. Due to the lower energy extraction, it is necessary to increase the battery capacity. Basically, it is important to keep the battery capacity as small as possible. Instead, the module surface should be increased.

From the economic evaluation it is evident that the largest costs stem for the battery. Here also the largest saving potential is available. From the calculated price per kWh is apparent that currently the system cannot be operated at competitive costs. Taking into account future developments in the electricity market the situation can change in the near future.

For the investment analysis a optimized system design is presented here. Following assumptions are made:

- The solar fraction reaches over 90 % during the summer months.
- The calculation is done for a lifespan of about 25 years.
- The expected lifetime of the solar modules is assumed to 25 years.
- The inverters are defined with a 15 years lifespan.
- The battery life (based on producer data) arises from the calculated load cycles
- For the batteries an annual price increase of 2 % was adopted.
- For the inverter in this calculation, no price increase was assumed
- Installation costs of € 500 per kW-peak were estimated
- Operating costs of 0.5 % of the investment costs.

[5] Böhm, et al.: Autarke Energieversorgung 2: KWK als Ergänzung zu PV und ST. FH-Wels(2011).

With this assumptions and the operation conditions described in previous chapters an amount of 2685 kWh per year can be covered by the system. Thus the annual solar fraction increases is 67%. The resulting cost for one kWh produced by the systems is 0.75 €.

With the current price of electricity from grid which is about 18 cent, the stand alone system cannot compete. Due to further developments, it may make sense to operate it as a hybrid system. This means that grid connection is available with which energy can be injected into the grid or consumed. If a high portion of energy consumption can be saved which results to the fact that the network load decreases.

6. Conclusion

- To reduce the fluctuations caused by consumer behavior it is necessary to install a demand-side-management system. This system avoids high load peaks and reduces the energy demand during times with weak solar radiation, at night or in times with deep charging states of the storage unit. With this high amount of direct used energy generated by the PV installation is reached.
- In addition the efficiency of the electrical devices is very important. Only high efficient devices should be used in stand-alone-systems. The use of efficient devices reduces the required storage unit size and the inverter power and therefore the system costs.
- The simulations showed that an optimum of the size of the storage unit and the size of the photovoltaic array exists for an certain application. Because the batteries are the most expensive components of the system, it is necessary to minimize the storage unit and to maximize the photovoltaic array till the optimum is reached.
- In the current situation, such systems cannot build and operated cheaper than grid supply. To increase the efficiency a surplus feeding of the electricity should be taken in consideration. Nevertheless stand-alone-hybrid-systems can reach interesting performance costs depending on the price development of electricity in the near future.

Acknowledgment

The authors gratefully acknowledge support of Company Banner /Linz for supply of batteries.