Solar Stand-Alone Power and Backup Power Supply

Basic information, applications and SMA solutions

Front cover:
30 kWp Hybrid Backup System in Ntarama, Ruanda,
to supply power to a vocational training center for solar technology
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1. Stand-Alone Renewable Energy Systems

According to EU estimates, there are more than a billion people in the world living without electricity. Due to high investment costs for expanding the public grids and low power requirements, it would be uneconomical to connect these remote areas to the utilities in the medium run. Under these circumstances stand-alone PV systems present a logical alternative.

Stand-alone PV systems are autonomous power grids being supplied with energy from a photovoltaic generator. Examples of such systems include electricity supply systems on islands, for isolated settlements or entire villages. According to EU estimates, approximately 300,000 farmsteads and buildings in Europe alone are not connected to the public power grid. In such cases, stand-alone photovoltaic systems are often the most economic solution.

Various constraints have to be taken into account when planning, designing, and selecting a stand-alone power system. In fact, the optimum design of an electricity supply system depends primarily on the following five factors:

1. Required connection power
2. Energy consumption
3. Type of power consumers
4. Period of use
5. Meteorological constraints

Alongside these technical aspects, there are also cultural, social, economic, and financial factors which need to be taken into account.

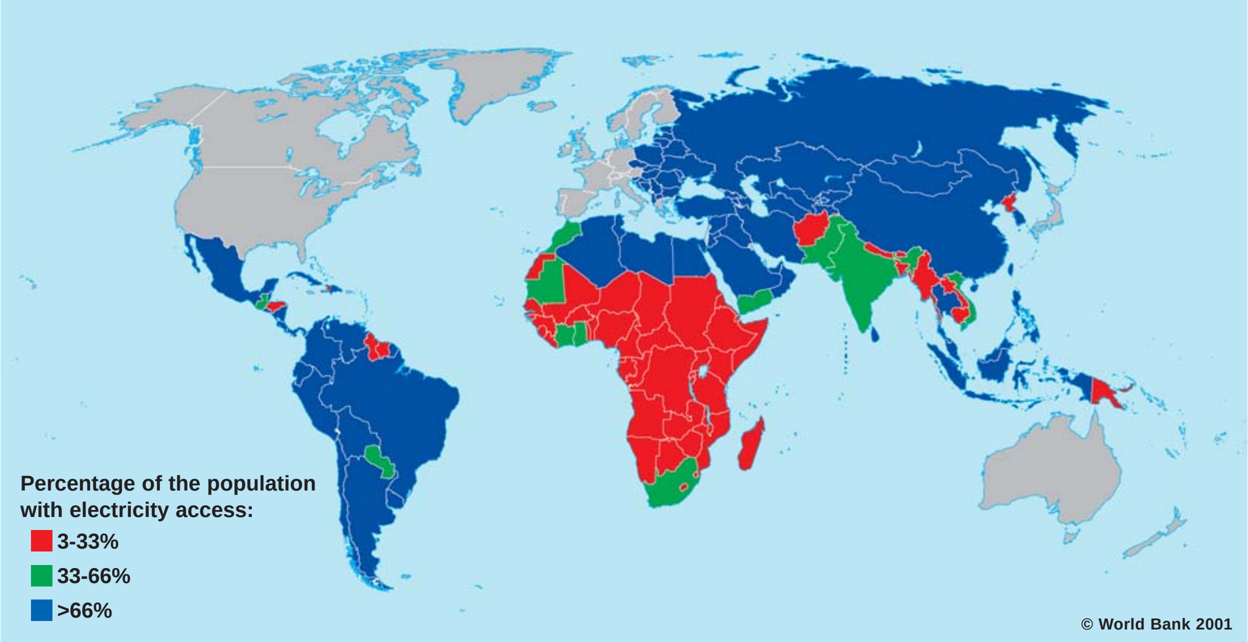


Fig. 1.1: Rates of electrification (Source: World Bank)

1.1 Components

The PV generator as the source of renewable energy is the crucial component of the stand-alone power system. Other available generators include those with combustion engines (e.g., diesel generators or cogeneration plants), as well as water and wind turbines.

Stand-alone power systems are generally differentiated according to their type of voltage (DC or AC). In DC coupled systems, the PV generator is connected via a special DC/DC charge controller (see Fig. 1.2). In AC coupled systems, a conventional PV inverter is used for feeding power into the grid (Fig. 1.4).

The battery or stand-alone power inverter is the heart of the AC coupled system. It ensures that generated and load power are balanced at all times. If too much energy is generated, the inverter stores this surplus energy in the batteries. If energy demand exceeds supply, the inverter discharges energy from the batteries.

The main differences between stand-alone inverters and PV inverters are shown in Table 1.1.

The Sunny Island Battery Inverter at a Glance

- Ideal for power supply systems from 2 kW to > 100 kW
- Flexible single- and/or three-phase
- Stackable
- Excellent overload characteristics
- Suitable for use in extreme climatic conditions
- Optimal battery management and state-of-charge recording to ensure long battery service life
- Low-cost integration of standard AC consumers, renewable power sources and generators
- Easy commissioning

A management system that includes battery, generator, and load management is absolutely essential for the optimum operation of a stand-alone supply system. This control function is integrated into the battery inverter. It simplifies the operation of the system and keeps investment costs down.

The Sunny Island battery inverter provides everything necessary for reliable system management. It can be used in a flexible manner and opens up completely new possibilities using AC coupling in the design of autonomous power systems.

	Photovoltaic Inverters	Stand-Alone Power Inverters
Direction of energy flow	unidirectional	bidirectional
Functions	MPP Tracking sinusoidal grid current	management of batteries, generators and loads; sinusoidal grid voltage
Overload capacity	approx. 110 %	approx. 300 % (short-circuit-proof)
Active / reactive power	feed-in of active power	loads with any power factorr
Typical DC voltage	125 V–750 V (string technology)	12 V, 24 V, 48 V

Table 1.1: Comparison of PV and stand-alone power inverters

1.2 System Design

Apart from power consumers such as lamps, radios, TVs, and refrigerators, a stand-alone PV system is made up of four basic components: a power generator (e.g., PV generator), a storage battery, a charge controller, and an inverter. These components can be coupled at various system levels – on the DC side, on the AC side, or in hybrid systems.

1.2.1 DC Coupling

In a DC coupled system, all loads and generators are coupled exclusively at the battery voltage level (see Fig. 1.2). A DC supply on the basis of a 12-Volt battery is particularly suitable for simple system constellations. Especially when the electricity is to be used primarily for lighting – such as in a solar home system (SHS) in the power range of a few hundred Watt. During daylight hours the battery stores the energy supplied by the PV generator. This energy is then available in the evening to power the lighting system. With the help of an additional small inverter, it is also possible to operate conventional AC power consumers in the DC system.

In general, it is advantageous if AC consumers can be utilized. These are available worldwide and can be purchased at low cost.

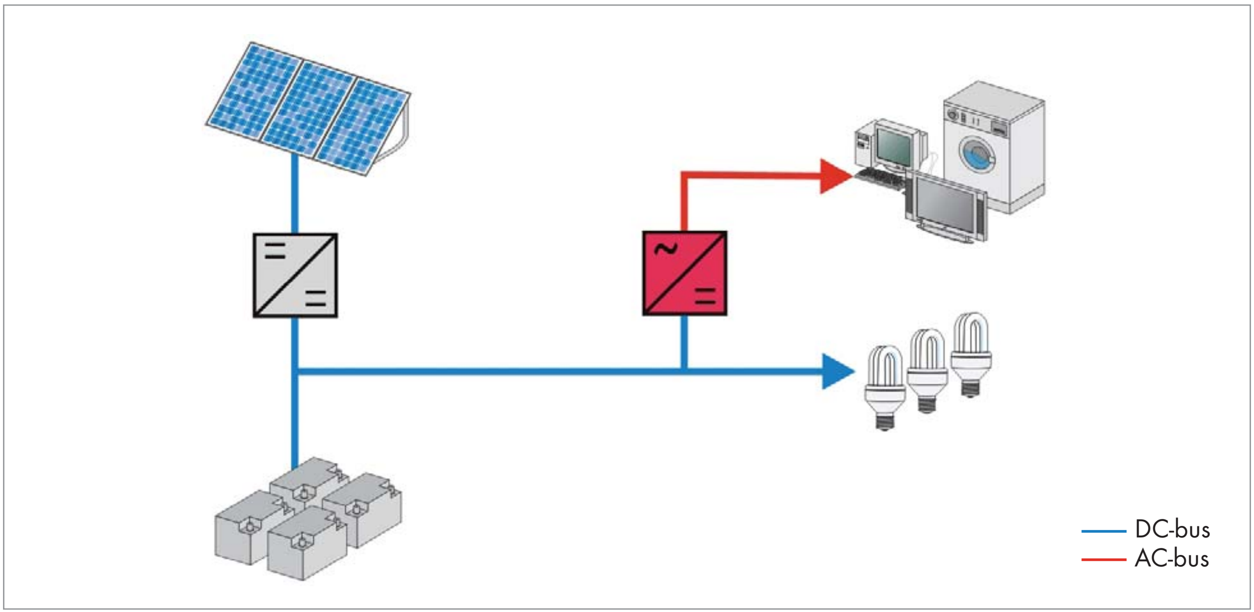


Fig. 1.2: Solar home system capable of providing alternating current

1.2.2 AC-DC Systems

Hybrid AC-DC systems are especially suitable for connecting mid-range AC power consumers with DC generators. With such systems, the battery on the DC side can be simultaneously charged via a combustion unit (see Fig. 1.3).

The demands on a hybrid system differ from those on a solar home system. Hybrid systems are used to supply remote power consumers and are able to handle higher energy requirements. Accordingly, such AC-DC systems are typically used in farmhouses, small businesses, and farmsteads.

The designer of an AC-DC system should take into account that the inverter capacity must correspond to the required energy consumption. Even when more energy is available from PV and wind sources, the inverter will limit the capacity supplied on the AC side.

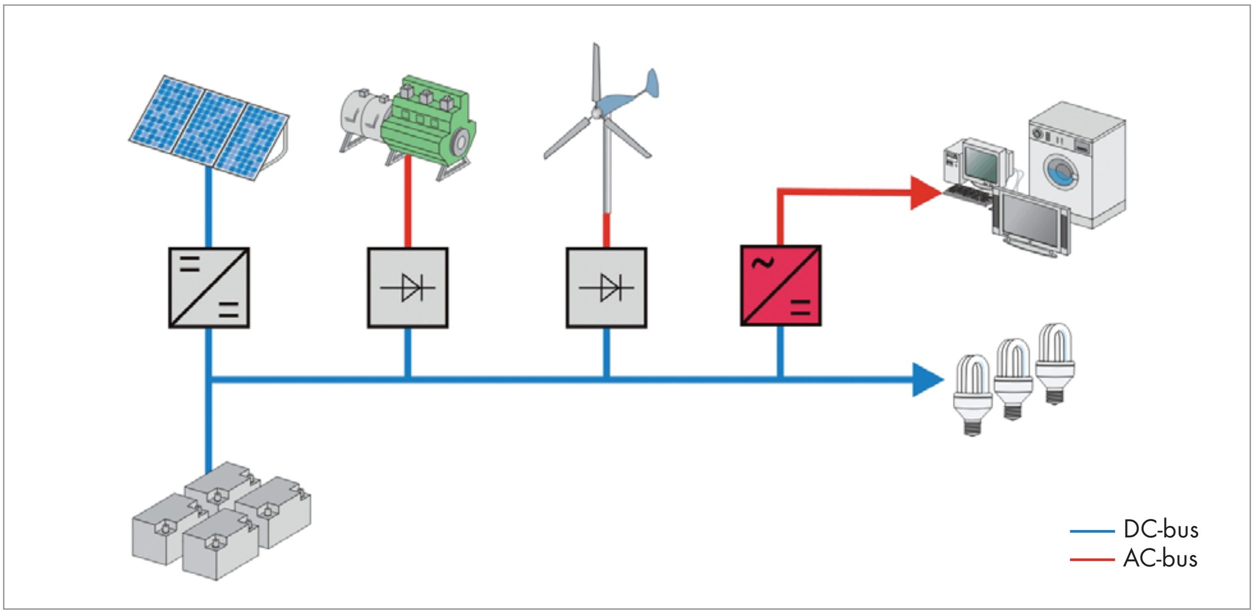


Fig. 1.3: Hybrid system with DC coupled components

1.2.3 AC Coupling

The connection of all power consumers and generators on the AC side (see Fig. 1.4) offers a decisive advantage: it enables systems to be built up or expanded with standardized components on a flexible, modular basis.

Renewable and conventional power sources can be combined, depending on the application and the available energy carrier. This is a particular advantage in situations where the grid structure is weak. The connected energy sources charge the batteries and supply energy when it is needed. If inverters and combustion units are intended for that purpose, a connection to the public grid is possible. The system can easily be expanded by adding further generators, thus enabling it to handle a rising energy demand. Additionally connected AC sources result in a real increase in capacity on the AC side.

AC coupled systems can be used to supply all power consumers. Hence, they are ideally suited for applications in rural areas of developing and newly industrialized countries.

In the medium power range (2 – 100 kW), the structure of such supply systems does not require any additional control or monitoring unit. Battery inverters such as the Sunny Island automatically check the availability of the grid and the system components. This simplifies the operation of the system and keeps investment costs down.

From an economic perspective, stand-alone power systems with a storage battery in the kW power range are considerably more cost-effective than systems which use diesel generators only. Even larger hybrid systems which use a diesel generator to avoid long-term battery storage can be operated at lower cost than stations working exclusively with diesel units. This can be attributed to the high cost of maintenance, short service life, and very poor partial load efficiency of diesel generators.

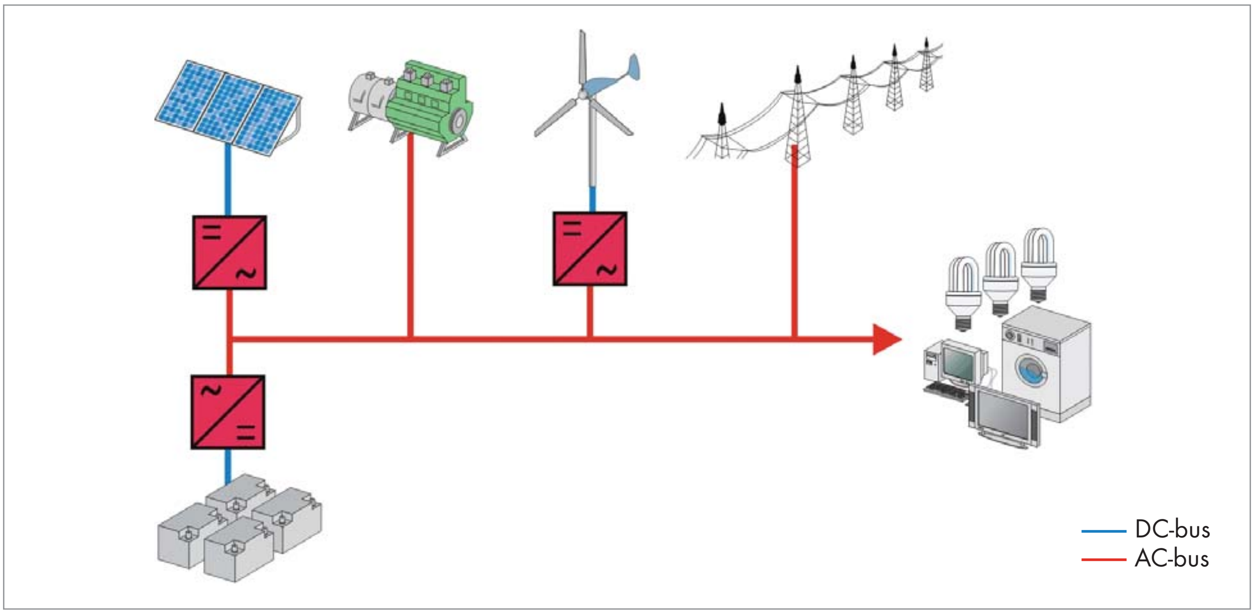


Fig. 1.4: Hybrid system with AC coupled components

Expandability and the type of connection of the individual components play a key role in off-grid power supply systems. The AC coupling with the Sunny Island enables power generators of all kinds as well as standard power consumers to be connected to the stand-alone power grid. The system is easy to expand both on the consumer and on the supply side (see Fig. 1.5).

Advantages of AC Coupling

- Structure 100 % compatible with the public grid
- Simple installation, since standard household installation components can be used
- Addition of power of all components feeding into the grid
- Scalable as desired, even for relatively large systems (from 2 kW up into the megawatt range)
- Easily expandable
- Combinable with net-parallel and isolated power generators (diesel units, small hydro-electric plants, wind turbines, etc.)
- Top reliability due to redundant system structure

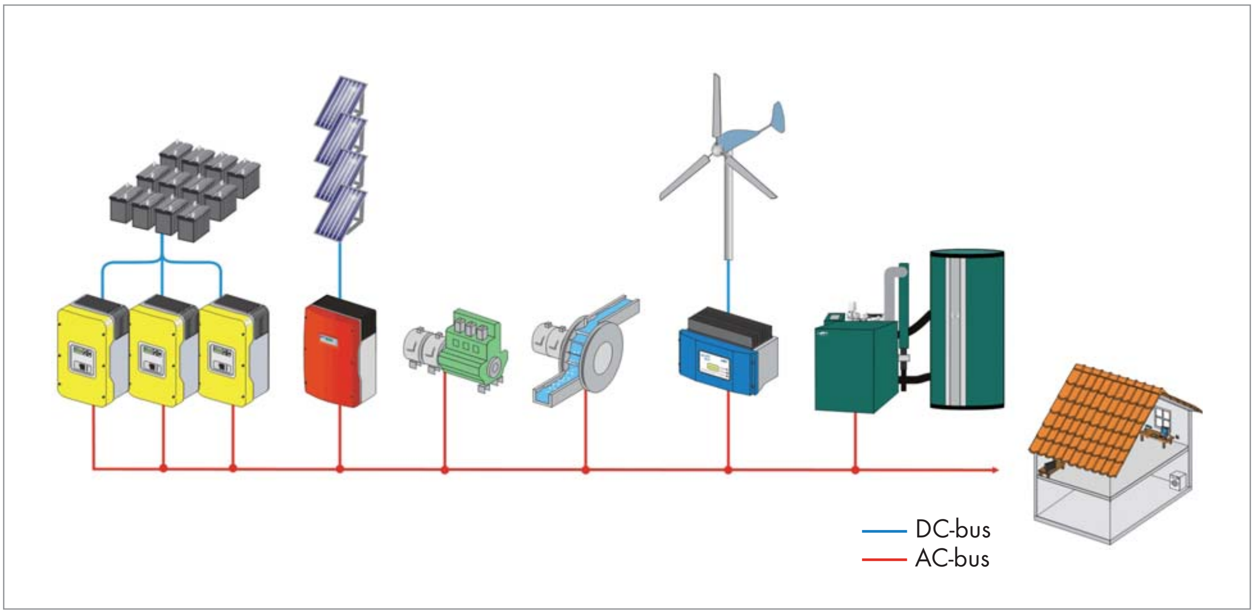


Fig. 1.5: Modular and flexible AC coupled hybrid system

1.3 Functionality

Stand-alone power inverters such as Sunny Island are connected to a battery bank and form the AC grid of the stand-alone power system. At the same time, they control the voltage and frequency on the AC side. Generators as well as power consumers are connected directly to the AC grid. Whenever there is a surplus of energy (e.g., when solar irradiation is high and consumption low), the stand-alone power inverter draws energy from the AC grid and uses it to charge the batteries. When there is an energy shortage (little or no solar irradiation and high consumption), Sunny Island uses the batteries to supply the grid (see Fig. 1.6).

Various power generators can be connected to the stand-alone power grid: PV plants with Sunny Boy inverters, wind turbines with Windy Boy inverters, hydroelectric power stations, and diesel generators. The latter can step in when the battery charge is low and there is not enough solar irradiation available for recharging.

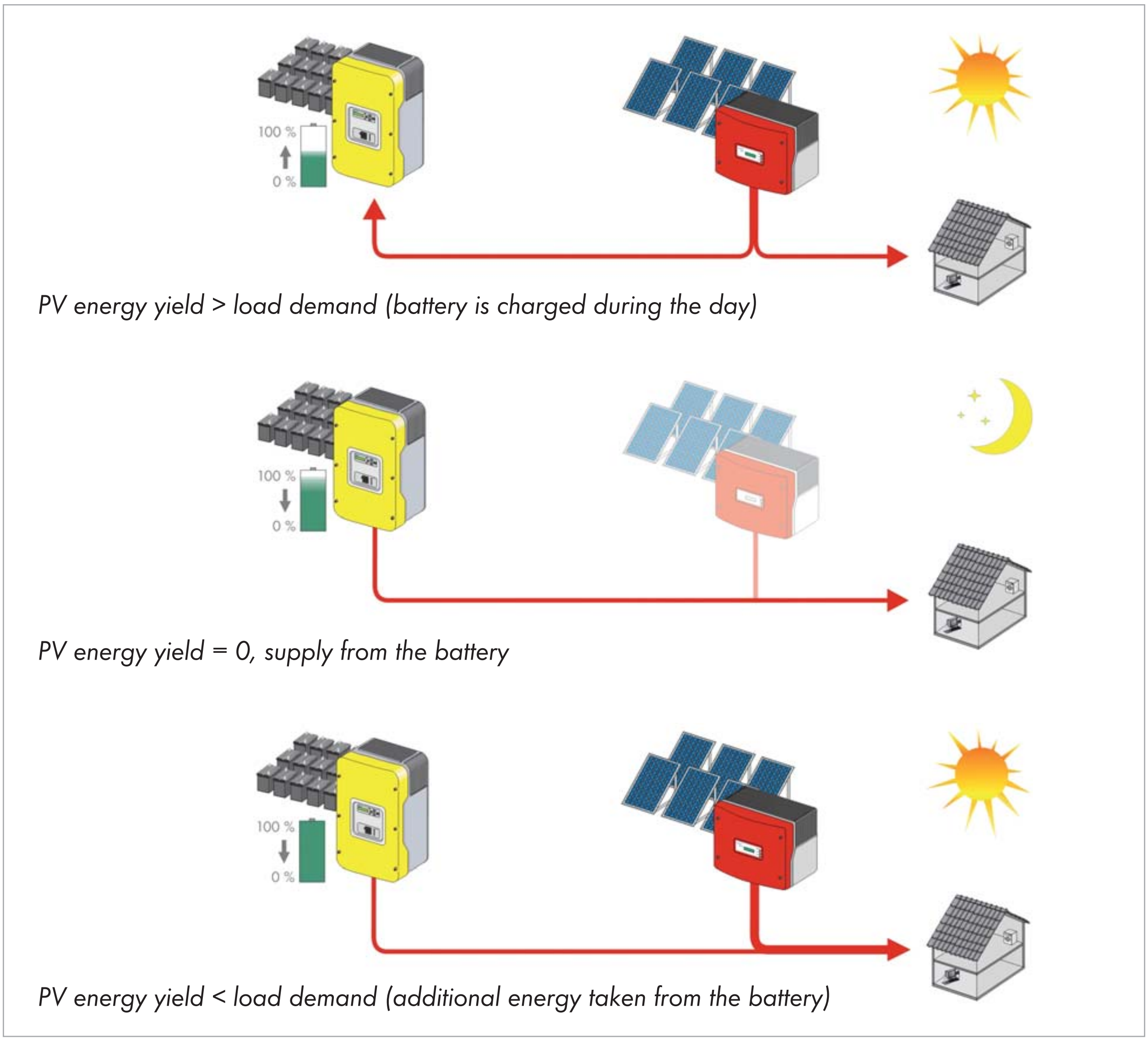
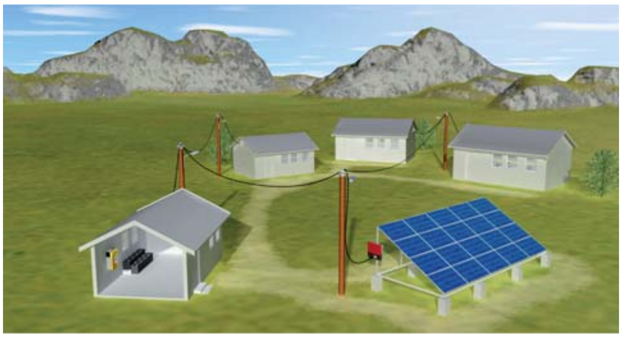


Fig. 1.6: PV energy yield and load demand

1.4 Growth and Connecting of Stand-Alone Power Systems



Stand-alone power grids with Sunny Island can be gradually expanded into large-scale systems as a result of the parallel connectability of all energy suppliers and consumers. They are particularly well suited for the supply of grid-isolated areas such as remote villages.

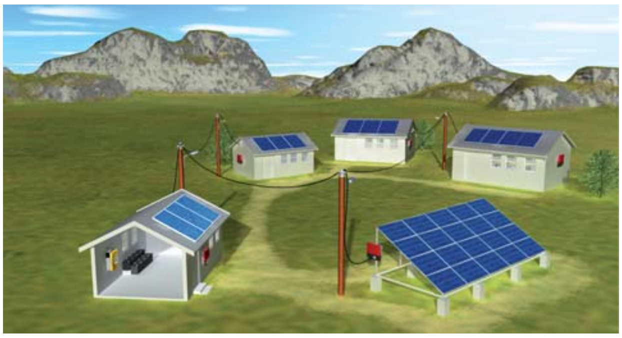


Fig. 1.7 shows the layout and the expansion possibilities for an AC coupled village power supply. The autonomous energy system can easily be expanded by further power generators when the power demand rises. One further advantage of the stand-alone power system: Thanks to the storage batteries, energy not needed during the day will be available at night, e.g., for street lighting.

Legend Fig. 1.7
1: PV generator
2: PV inverter Sunny Boy
3: Battery inverter Sunny Island
4: Storage battery
5: Generator
6: Wind turbine

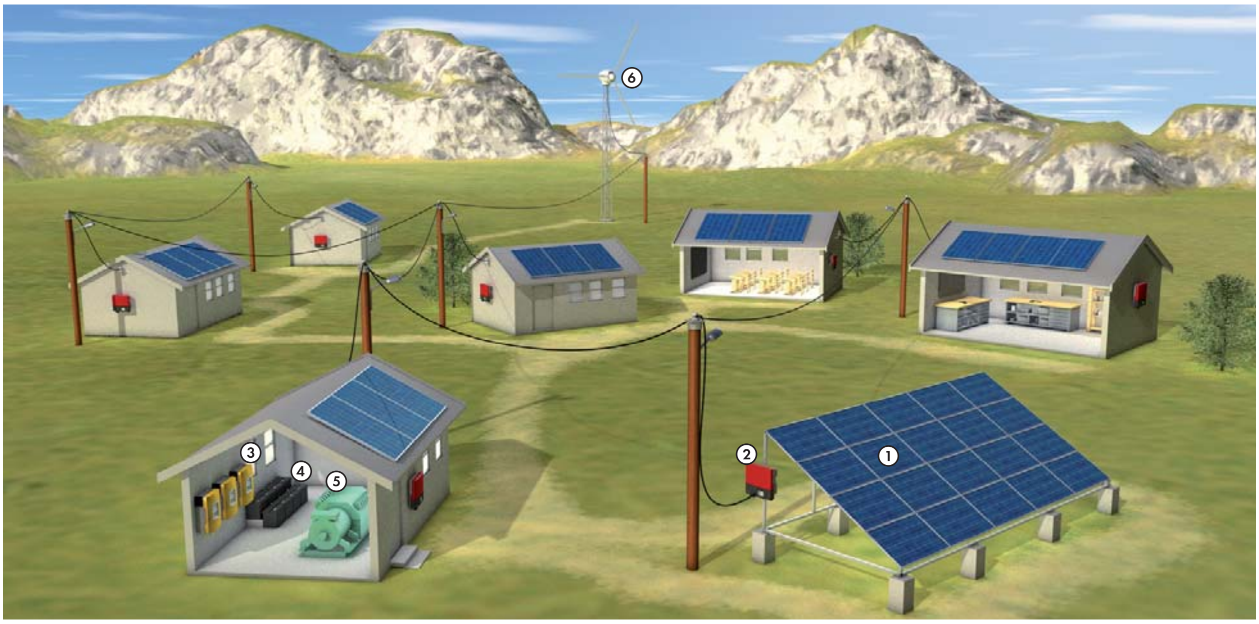


Fig. 1.7: Expansion options of an AC coupled hybrid system for a village electricity supply

In order to ensure a maximum level of system stability in larger systems, Sunny Island inverters are installed in so-called clusters. Here, up to three devices (as a three-phase system) or even four devices (single-phase, operated in parallel) together with the battery comprise a unit. In order to achieve the desired output, several units can be connected in parallel (thus forming a cluster). If one battery fails, it does not affect the entire system (see Fig. 1.8).

1.5 Sunny Backup – SMA's Emergency Power Supply

While in stand-alone power systems grid connection is redundant, the Sunny Backup-System allows grid-connected PV systems to achieve temporary independence from the public power grid. In the event of a power outage, the backup system continues to provide electricity to the in-house grid.

The system basically consists of the Sunny Backup inverter, a PV system, and a storage battery. During normal operation, one or more solar inverters feed electricity from the PV system into the public grid. The Sunny Backup-System will only activate in the event of a grid failure or outage. The switching mechanism will then disconnect both PV system and power consumers from the public grid in accordance with the applicable standards, while supply to the in-house grid continues from the battery. In the role of system manager, the Sunny Backup device coordinates all switching operations. Thus, it provides reliable backup for every grid failure.

In this instance, the PV system acts as a power source for the direct supply of the consumers and

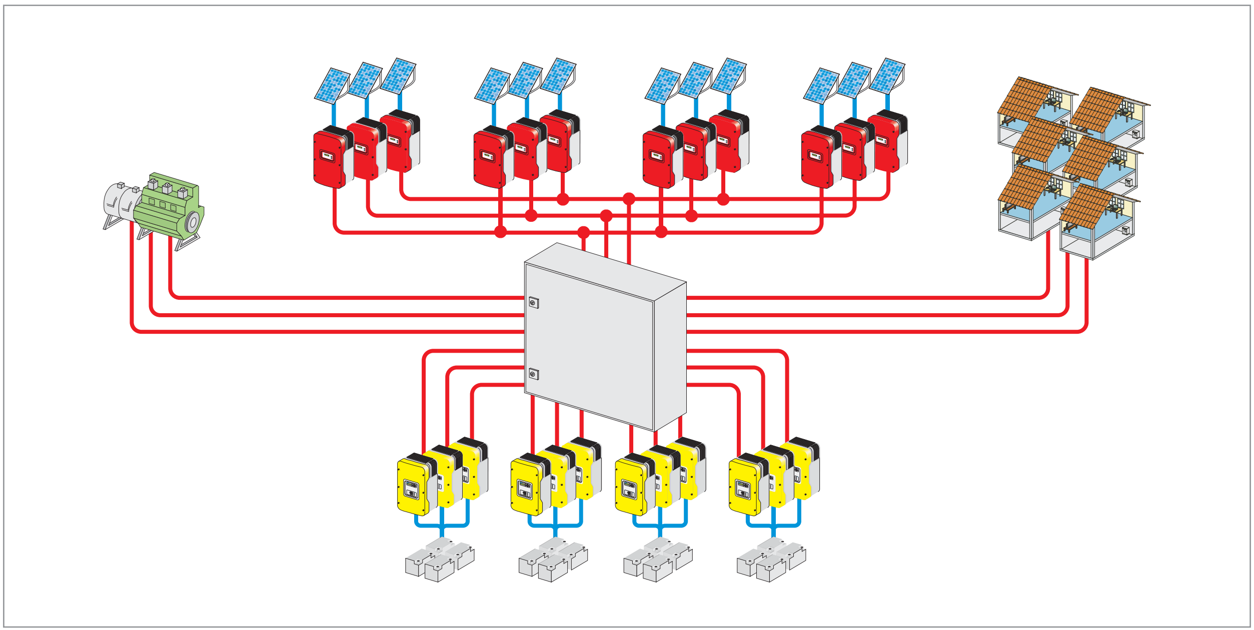


Fig. 1.8: AC coupled hybrid system with four clusters connected to a Multicluster Box

for charging the battery. In this way, consumers can be supplied with power over long periods of operation, even in the event of a power outage. If locally available renewable power sources can be linked in, a longer period of autonomy will be achieved, even when battery capacities are limited. Consistent use of AC coupling is the requisement for smooth interaction between the Sunny Backup-System and solar inverters.

As an ideal combination of public grid and stand-alone operation, the Sunny Backup-System is attracting the interest of a growing number of operators. It offers outstanding alternatives in developing and newly industrialized countries with unstable power grids. It can represent a useful supplement to the public grid. According to expert opinion, prolonged blackouts and temporary power cuts are predicted to increase throughout Europe.

The Sunny Backup Inverter at a Glance

- Ideal for power supply systems from 2 kW to > 100 kW
- Can be integrated in new and existing PV systems
- Pre-configured set
- Compact, low-cost switching mechanism
- Small-size battery due to integration of PV system
- Power supply and battery charging via the grid
- Unaffected high PV efficiency
- Automatic switchover to backup supply in approx. 20 milliseconds

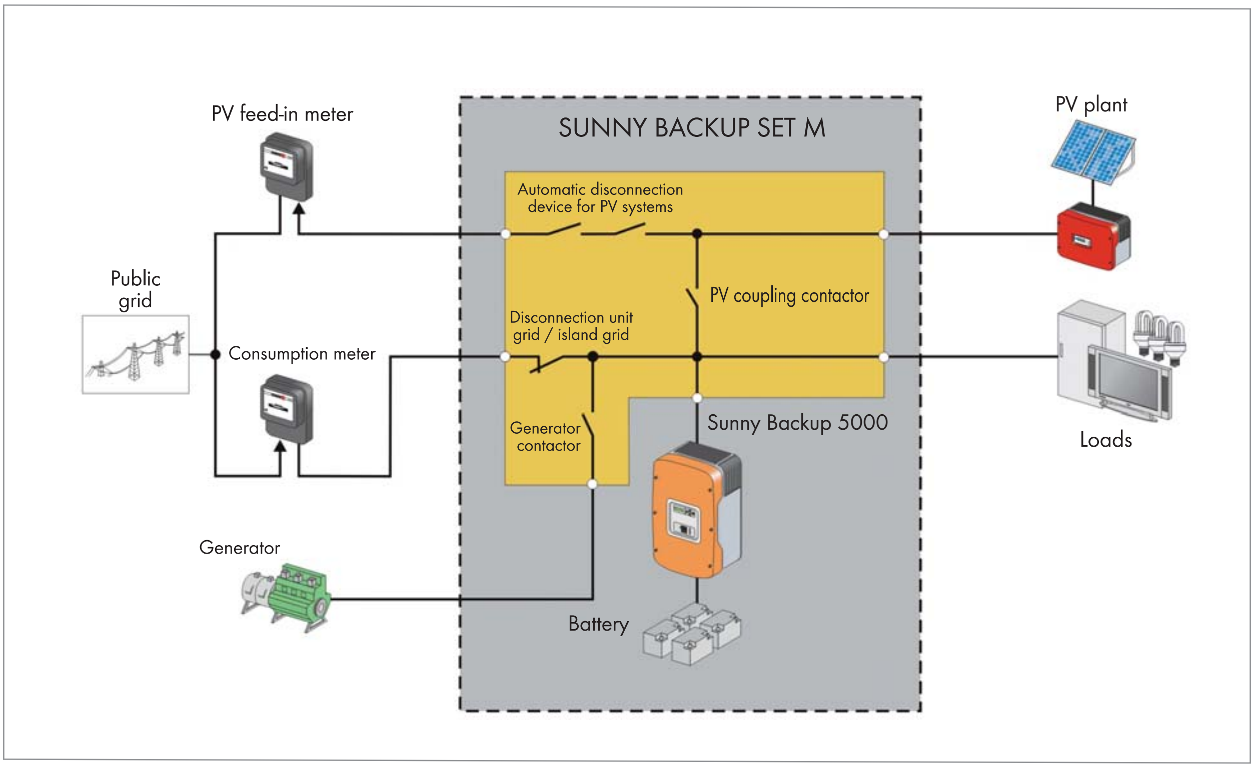


Fig. 1.9: The SMA backup solution

2. Stand-Alone Power Inverters

The stand-alone power inverter Sunny Island is the first modular battery inverter to enable various power generators (PV systems, wind turbines, power generating units, cogeneration plants, mini hydro-electric power plants) to be connected on the AC side (AC coupling).

The stand-alone power inverter is equipped with various management systems which guarantee the stable operation of the power supply system. Battery, generator, power and load management complement each other to provide a comprehensive system management. All the necessary variables are measured or calculated by Sunny Island. This ensures that no switching activity or setpoint alteration will be left to chance.

In order to enable the parallel operation of the AC coupled voltage sources without involving any communication, the so-called "droop mode" (SelfSync®) is used.

This method uses active and reactive power statics as a basis for coordinating the performance of the various coupled converters (see Fig. 2.1). To achieve optimum power flow, the grid parameters voltage and frequency are specifically influenced.

Each converter operates by using a cascade controller as its voltage source. In this way, the consumption and output of active power of each individual parallel converter is independently controlled as a function of the stand-alone power grid frequency. If the frequency increases due to a sudden reduction in load, all converters will reduce their power input, and thus the system will remain balanced.

These control algorithms enable a fast reaction to the typical power fluctuations in the stand-alone power grid. They are available for all relevant grid configurations (400 V or 230 V/50 Hz and 120 V/60 Hz).

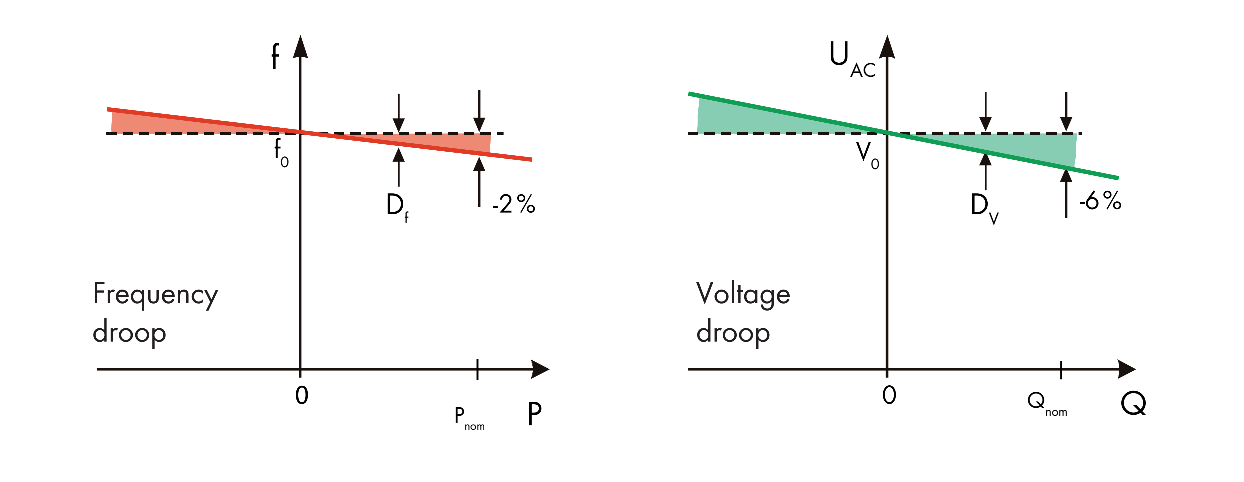


Fig. 2.1: Control algorithm in the SMA stand-alone power inverter (SelfSync®)

2.1 Safety Functions

The stand-alone power inverter has been optimized for both thermal and electrical overload conditions. It adjusts the maximum power in direct response to environmental conditions. With the patented cooling system OptiCool (Fig. 2.2), SMA is now offering a technical solution which combines both passive and active cooling. This intelligent temperature management function is made up of a two-chamber system with a water-tight compartment for the electronics and an air-flow compartment containing the relevant heat sources. This ensures excellent protection and at the same time unique overload performance and optimum reliability.

In the event of high inrush currents soft-start functions are deployed: in the Sunny Island 5048, for instance, the overcurrent is limited to 100 A for the first 0.1 seconds. For up to three seconds the inverter supplies 2.5 times the rated current. Earliest after this period – e.g., if there is a lasting short circuit – the device will be switched off for safety reasons. 16 A circuit breakers with DIT rating B are triggered within 100 ms. This complies with the well-established safety regulations for net-parallel installations.

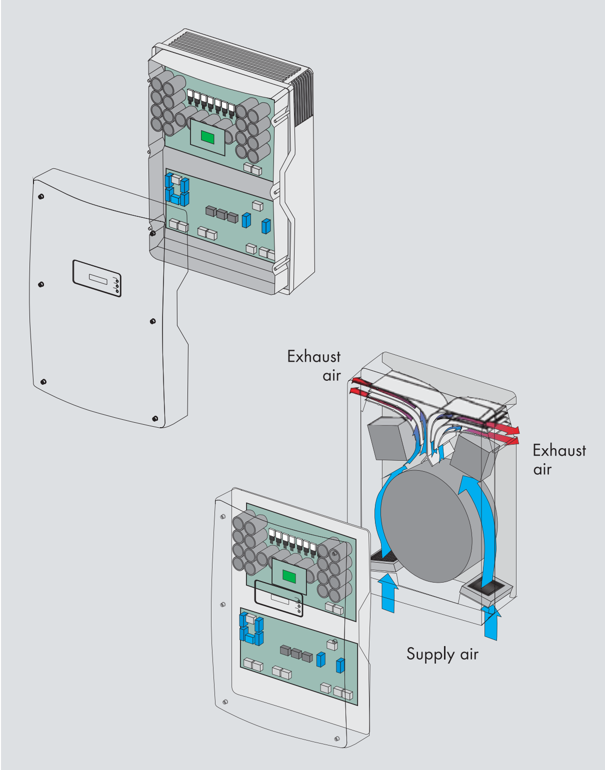


Fig. 2.2: The OptiCool cooling system enables deployment under extreme environmental conditions

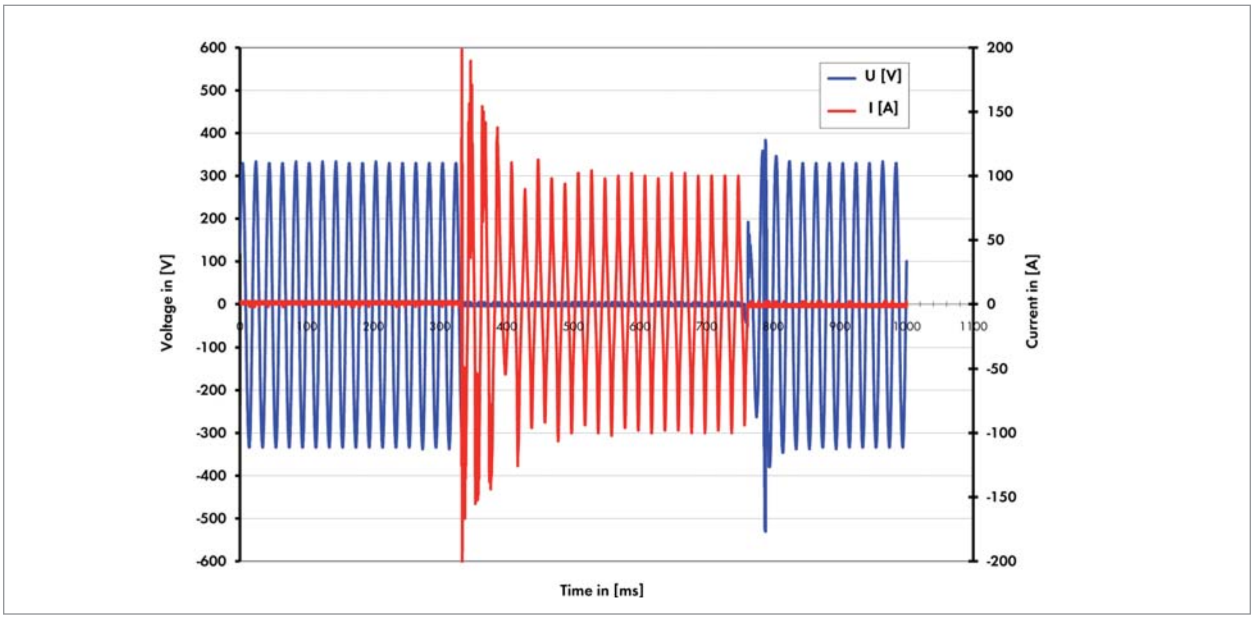


Fig. 2.3: Voltage and current curves of Sunny Island 5048, during and after the occurrence of a short circuit

2.2 Operational and User Control

The fundamental control concept of the stand-alone power inverter (e.g., SI 5058, SI 2224) is the „Single Point of Operation" (SPO). All adjustments, switching sequences and important system variables can be brought together and displayed or amended on a single screen.

SPO allows a compact system overview and makes it possible to adjust parallel units and connected charge controllers from one device. Information about external power sources or loads can be accessed since all automatic switching operations are likewise activated by the stand-alone power inverter. Via an internal communication system, all relevant information can be exchanged between system components which support this function.

In order to make the installation and control of the Sunny Island System as easy as possible for installer and users, SMA has developed a "Quick Configuration Guide." By entering the answers to just a few questions via the menu, the installer can configure the entire system. From these approx. six simple settings, the inverter can generate all missing default values, thereby ensuring reliable system operation.

2.3 Data Collection and Data Storage

A substantial part of the internal control menu focuses on the history of all the operation modes that have ever occurred. Peak values as well as important data and events are stored in a permanent internal memory. An integrated data acquisition system carries out all measurements, calculations, and evaluations. In this way, a comprehensive picture of all processes, from charging to automatic load shedding, can be compiled.

All important data is stored on a flash memory card. The user can choose between memory card sizes of 128 MB and 2 GB. The data is stored in accordance with the FIFO (first in – first out) procedure. Thus, the most recent data are made available not only to the user, but also to the SMA support team.

It is very easy to extend the spectrum of the Sunny Island data acquisition – using SMA communication products. For example, simple and comprehensive remote monitoring is made possible by the data logger Sunny WebBox.

3. Power Generators in the Stand-Alone Power Grid

Stand-alone power grids are set up primarily to supply power to off-grid loads. This energy must be made available in a form which is suitable for use by power consumers. That means for AC coupled stand-alone power grids, that all energy sources work on the basis of defined voltage and frequency levels (e.g., 230 V/50 Hz). Power generators, currently obtainable on the market, are usually pre-configured to the given country-specific settings. In some countries such as Brazil and Japan, however, it is advisable to verify this data very carefully. For example, in Japan 127 V and 230 V are equally common – and at different frequencies, too (50 Hz or 60 Hz).

The power suppliers satisfy primarily the direct energy demand of the consumers. Energy which is not consumed directly charges the batteries and can be retrieved as required at a later time. Thus, the energy flow depends to a crucial extent on the behavior of the power consumers. In general, power sources can be divided into renewable resources and sources based on fossil fuels.

3.1 Inverters for Photovoltaics

The function of a PV inverter basically consists of converting the direct current provided by the solar modules into sinusoidal AC current. In this process, the device has the task of synchronizing the wave form of the available current and voltage to the frequency of the stand-alone power grid. Common PV inverters, such as the SMA Sunny Boy, determine the operating point with the greatest possible power output (Maximum Power Point – MPP) and track it during operation, thereby ensuring the greatest possible energy yield.

In stand-alone power systems power outputs ranging up to 100 kW are of primary significance.

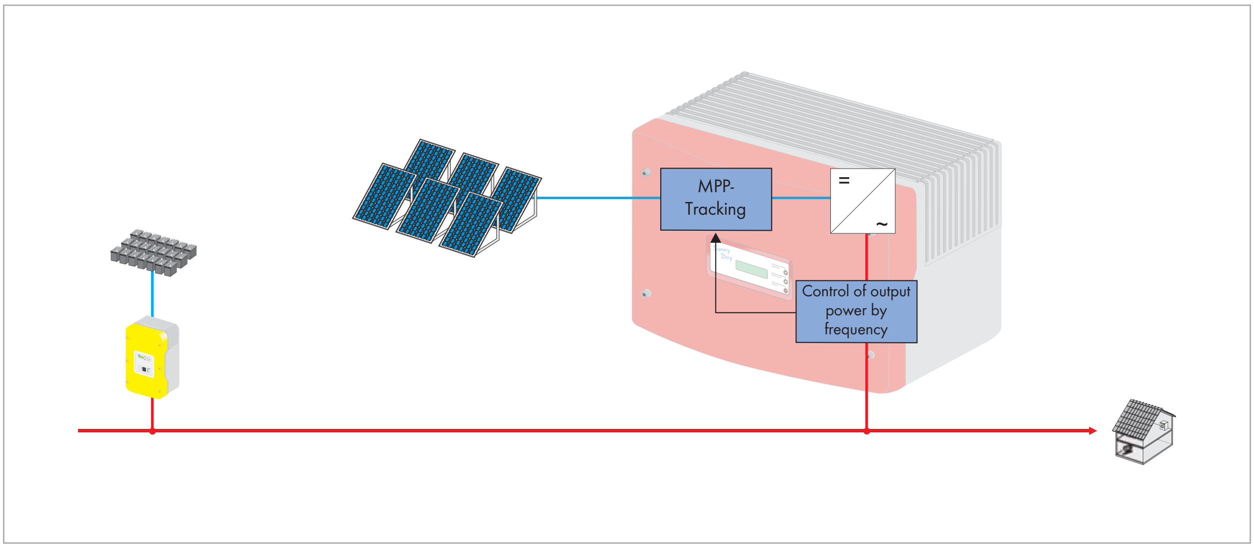


Fig. 3.1: The string inverter Sunny Boy in an stand-alone power system

SMA's Sunny Boy and Sunny Mini Central models are ideally suited for use in systems in this size spectrum. They are popular as a result of their first class efficiency factors, user friendliness, and reliability.

Sunny Boy and Sunny Mini Central are the only solar inverters with the ability to "interpret" the frequency level in the stand-alone power grid. In the same way as large power plants in the public grid, they are able to adjust to the given energy demand based on the measured frequency – i.e., to regulate the energy flow of the stand-alone power grid. They can be used without any problem both in single-phase and three-phase grids. A precise layout can be compiled with the "Sunny Design" program. This will give you information not only on the layout and orientation of the inverter and modules, but also on cable cross sections and the respective optimum operating point. Sunny Design can be downloaded from **www.SMA.de** free of charge.

3.2 Inverters for Wind Turbines

The primary task is to convert the direct current delivered by the wind turbine into alternating current. Neither single-phase nor three-phase grids present any problem – the SMA Windy Boy, too, can be installed in any SMA stand-alone power grid. Just like the Sunny Boy, the Windy Boy can adjust to the current energy demand of the stand-alone power grid, thus preventing an over-supply of energy. To increase capacity for large wind turbines, these devices can also be switched for single-phase in-parallel operation.

The Windy Boy Protection Box connected in series to the Windy Boy provides optimum protection and guarantees the smooth operation of the system. The Protection Box is equipped with a three-phase rectifier and limits surplus voltage and power from the wind generator, redirecting it into a load resistor.

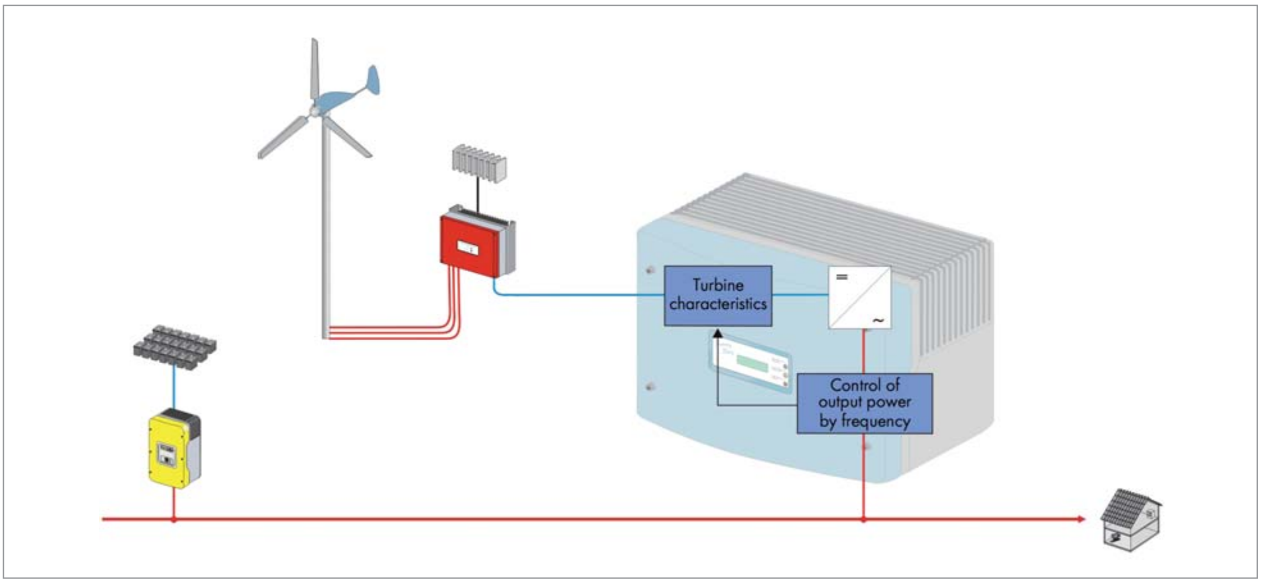


Fig. 3.2: Windy Boy inverter with Windy Boy Protection Box for small wind turbines in a stand-alone power system

3.3 Inverters for Water Turbines

Water turbines can also easily be integrated into SMA stand-alone power systems. Basically, a distinction can be made between water turbines with asynchronous generators and those with synchronous generators. Asynchronous generators with a power output of up to 5 kW can be integrated in simple three-phase systems. To do this, it is sufficient to connect them directly. Turbines with permanent magnet synchronous generators can be linked in by means of the Windy Boy inverters mentioned above.

With the wind turbine characteristics stored in their software, Windy Boy inverters are ideally suited for application in hydroelectric power systems as well. Synchronous generators which have their own voltage and frequency permanent control can be integrated in larger systems by means of an appropriate synchronizing device.

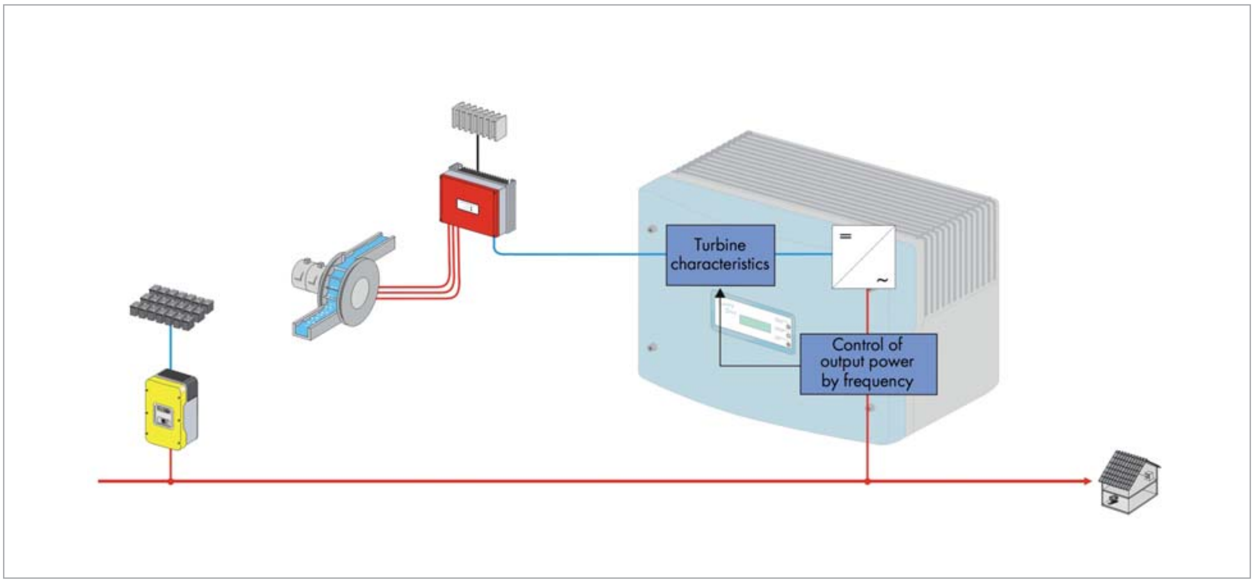


Fig. 3.3: Windy Boy inverter with Windy Boy Protection Box for small hydroelectric plants in a stand-alone power system

3.4 Cogeneration (Combined Heat and Power Plants)

Cogeneration plants running on diesel or non-fossil fuels are combustion engines that not only generate electrical power, but also the waste heat from the engine and the exhaust system are utilized for purposes such as water heating. Based on performance class, so-called mini cogeneration units are primarily suited for deployment in SMA stand-alone power systems. Grid-forming cogeneration plants are integrated in stand-alone power grids like conventional diesel generators, and are started and stopped by Sunny Island. They can also act as standby power units due to their synchronous generators. In the event of a power outage in the stand-alone power grid, the cogeneration plant itself can form a grid and continue to supply power to the loads. Small cogeneration plants are mostly intended for grid-connected operation. In this operation mode, they are connected to existing power grids while feeding power current regulated into it. They are equipped with asynchronous generators and therefore cannot form a grid of their own.

SMA Solar Technology AG has collaborated with PowerPlus Technologies GmbH to develop the EcoIsland system, consisting of a Sunny Island and an EcoPower cogeneration plant. These perfectly coordinated devices comprise a reliable stand-alone power grid in areas where heat recovery plays a significant role.

For further information please go to:
http://www.ecopower.de/ecopower-mini-bhkw/anlagen-und-systeme/ecoisland.html

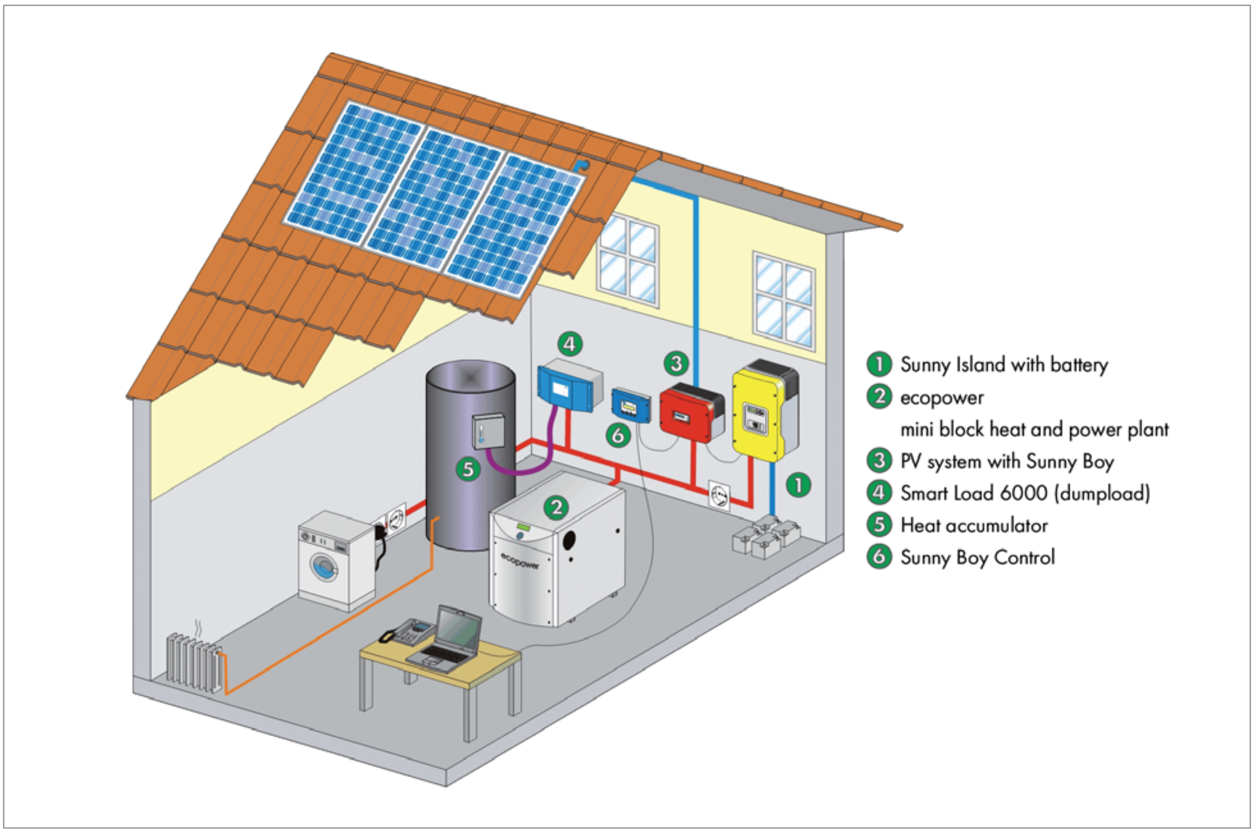


Fig. 3.4: EcoIsland system with PV plant and thermal storage system

3.5 Inverters for Fuel Cells

With its Hydro Boy, SMA offers an optimal way to integrate fuel cells in a Sunny Island System. The claim in regard to fuel cells, namely that they work with very high current and relatively low voltage, makes a device like Hydro Boy absolutely essential. Just like the Sunny Boy, it has the ability to adjust to the prevailing energy conditions in the stand-alone power grid.

Hydro Boy inverters are available in the standard sizes of 1.1 kW and 1.3 kW, and can also be custom-manufactured.

Today, fuel cells are produced in very different voltage and current ranges. Therefore, care must be taken to ensure compatibility with the Hydro Boy. Fuel cells can also be integrated in Sunny Island Systems on the DC, i.e. battery side. In this case, they serve to charge the battery directly, and if necessary can supply energy from the DC side to the AC side via the Sunny Island.

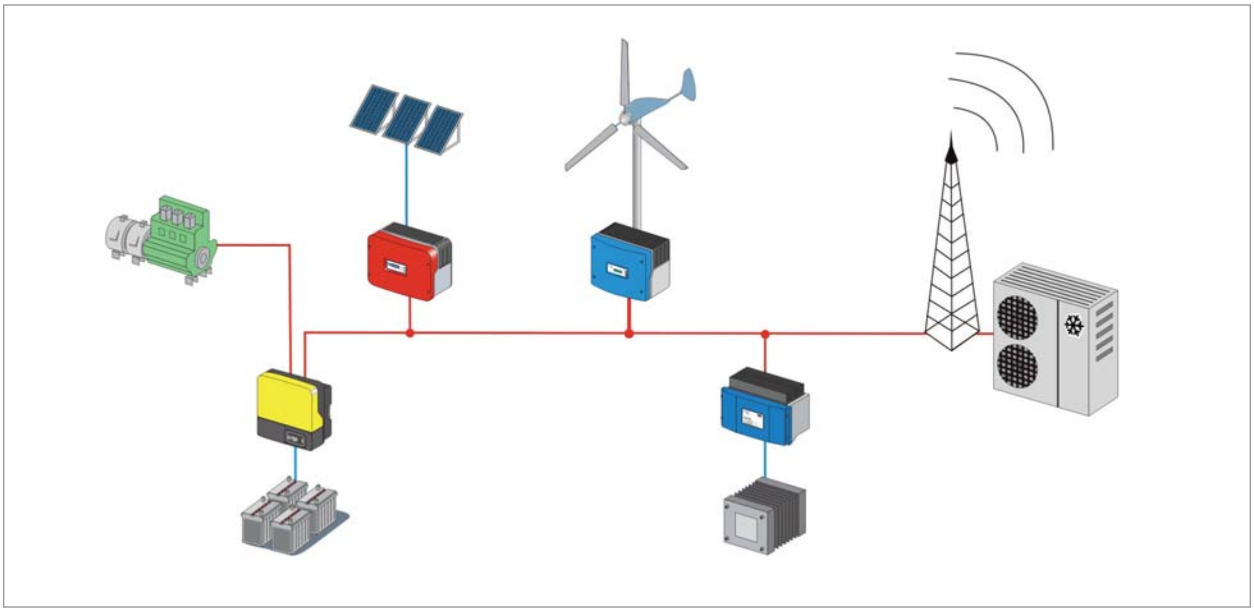


Fig. 3.5: Hydro Boy inverter for fuel-cell application in the stand-alone power system

3.6 Combustion Generator Sets

Combustion generator sets are a combination of a combustion engine and a power generator. They first convert the energy stored in the fuel into mechanical energy which is in turn used to generate electricity.

There are various design options for integrating both the combustion engine and the power generator into combustion gensets. These units are often integrated in hybrid systems in the form of backup generators in order to optimize the renewable generator and storage values, and also to improve the seasonal availability of the energy in the supply system. Fuel availability and engine efficiency are two significant factors which must be taken into account when designing a hybrid system. Thus, any sub-optimal construction of the combustion gensets can result in substantial operational and maintenance costs – for example, due to increased fuel consumption. Typically, combustion gensets have a remote start-up option. Based on predefined variables, they can be switched on and off selectively. Currently, units with manual start/stop function are widely available on the market or are already in operation. For such units SMA can offer the GenMan generator manager which adds on the remote start-up function.

Today, diesel generators also play an important role in hybrid renewable energy systems. What may seem paradoxical about this is quickly explained: Let us suppose a system were to be supplied entirely by solar energy. In this case you would need to install a sufficient number of solar modules to meet the power demand during the season with the least solar irradiation, e.g., for Central Europe in the winter. A system such as this cannot be an economically viable proposal due to the enormous PV generator needed. By integrating a diesel generator, we are using an energy source which is readily available at short notice. As a result, the size of the solar plant required is disproportionately reduced.

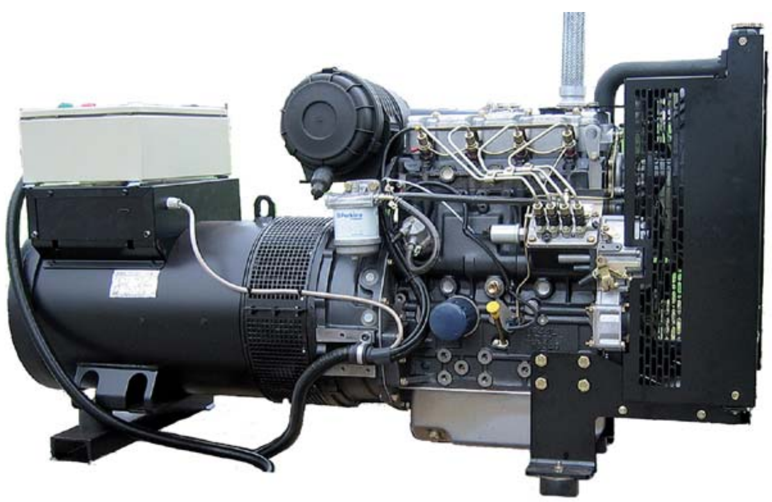


Fig. 3.6: Generator running on vegetable oil

4. Operational Control in Stand-Alone Power Systems

To date, operational control has played only a subordinate role in most hybrid systems. Plant operation is controlled by fixed threshold values which are preset in the charge controller or the battery inverter. The combustion unit is switched on or off depending on the condition of the battery. In the simplest case, fixed voltage limit values are used here exclusively. However, there are several limitations inherent in this technology. When battery load is very high, the internal resistance of the cells will trigger premature startup of the generator. In the case of minor discharge currents, the battery will often be deep discharged. The battery is therefore neither used to full capacity nor protected against excessive discharge. For this reason, newer generations of devices already use current-compensated voltage thresholds.

A reliable information basis for controlling plant operation is the battery's state of charge, but this information cannot be recorded by direct metrological procedures. In order to determine the precise state of charge of a battery we need calculation algorithms, which, however, vary greatly in their calculation accuracy. To date, only a few manufacturers of battery inverters have integrated algorithms to determine state of charge into their devices.

In addition to the determination of state of charge, another key function for achieving long battery service life in hybrid systems is charge control. Charge control requires regular full and equalization charging with significantly increased charging periods. To date, only a few manufacturers have integrated automatic full and equalization charging into their devices.

If the fuel consumption of the combustion unit is to be kept low, the unit must be efficiently and consistently charged to capacity. Accordingly, the generator must not be dimensioned larger than the battery

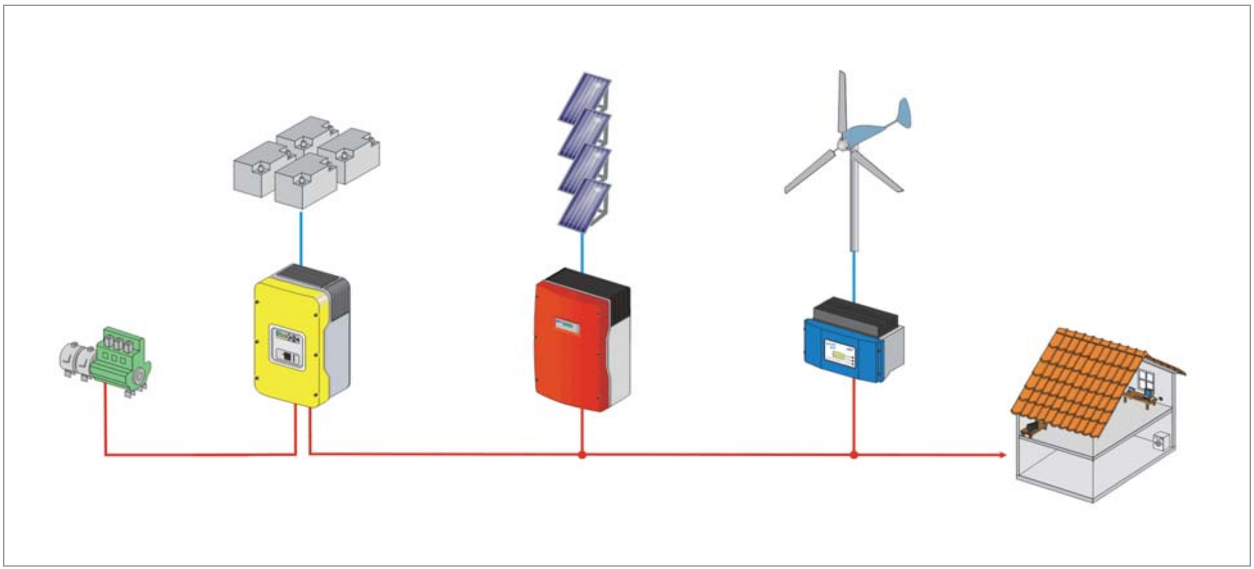


Fig. 4.1: Layout of a typical hybrid renewable energy system

inverter. Since energy consumption is subject to large fluctuations, the battery inverter must control the power output from the generator and constantly adjust its charging capacity. Reactive power management will be necessary if you also need to be able to charge reliably from small generators. At the same time, unnecessary reactive currents which impair the efficiency of the system must be avoided.

4.1 Tasks and Objectives

PV hybrid systems (see Fig. 4.1) consist of two or more power-generating and supply units, such as PV and wind turbine systems, hydroelectric power plants, or combustion gensets. Frequently, several such generators are connected in parallel.

With the exception of combustion gensets, the generators can only be controlled under certain conditions, or not at all. For this reason, a battery is always integrated in a hybrid system to act as energy and power buffer. The storage battery performs certain key functions. At times of a supply surplus the battery absorbs the energy which cannot be consumed at the time. When not enough energy is being produced to meet demand, the battery releases this energy. However, there are limits to the amount of storable energy and power. Furthermore, the battery is subject to aging processes which are highly dependent on the charging technique employed. Therefore, this makes battery management the crucial factor in the entire process of operational control. Without intelligent charge control and effective protection against total discharge, typical lead acid storage batteries only provide a very short service life.

The service life and efficiency of combustion gensets also exhibit a strong dependence on prevailing and frequently occurring operational conditions. Thus, typical diesel engines for electricity generation as a rule reach maximum efficiency at 100 % of their nominal power (see Fig. 4.2). At around 50 % of nominal power, efficiency is already 20 % less. At generator loads below 50 %, efficiency drops off very steeply.

The operational control of hybrid systems has the following three basic tasks:

- To keep the system securely operational so that the loads can be reliably supplied with electric power
- To minimize fuel and maintenance costs
- To optimize the life of the battery and generator

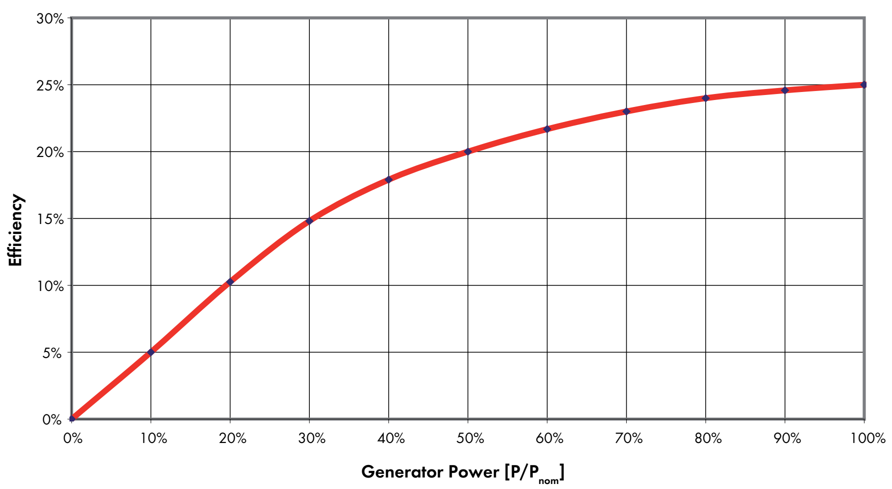


Fig. 4.2: Efficiency curve of a typical small diesel generator

4.2 Optimum Operational Control: Sunny Island's Charge Control

Battery inverters made by SMA Solar Technology AG work with a very precise equalization algorithm which can be adjusted to different battery types and to the age of the batteries. State-of-charge monitoring has been added by connecting an external current measurement shunt. This makes it possible to monitor and control DC power consumers or power suppliers on the battery side.

The Sunny Island battery inverter has a 3-stage charge control with automatic full and equalization charging (as shown in Fig. 4.3). This ensures that both over- and undercharging are reliably prevented.

Fig. 4.4 shows the charge control and state-of-charge recording in a hybrid PV system in Greece. After full charging for about 5 hours, only one trickle charge is carried out on the following day.

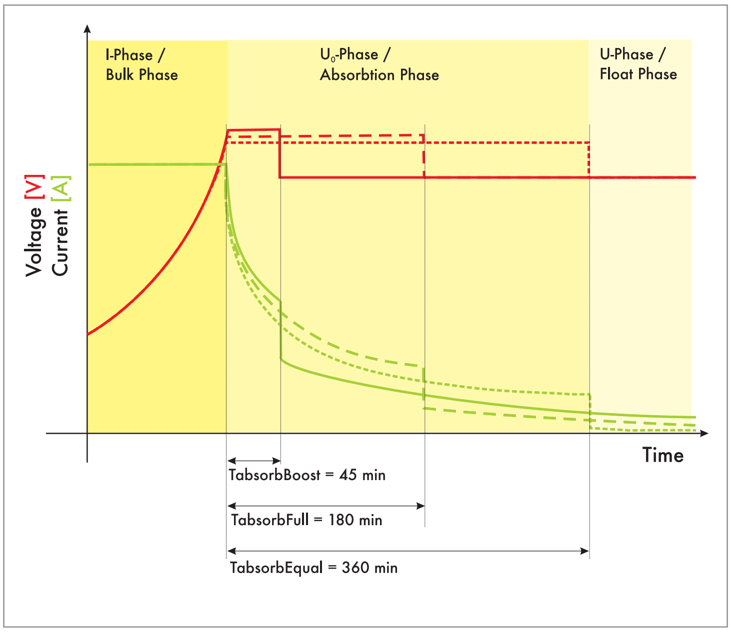


Fig. 4.3: Various phases of charge control in the battery inverter Sunny Island 5048

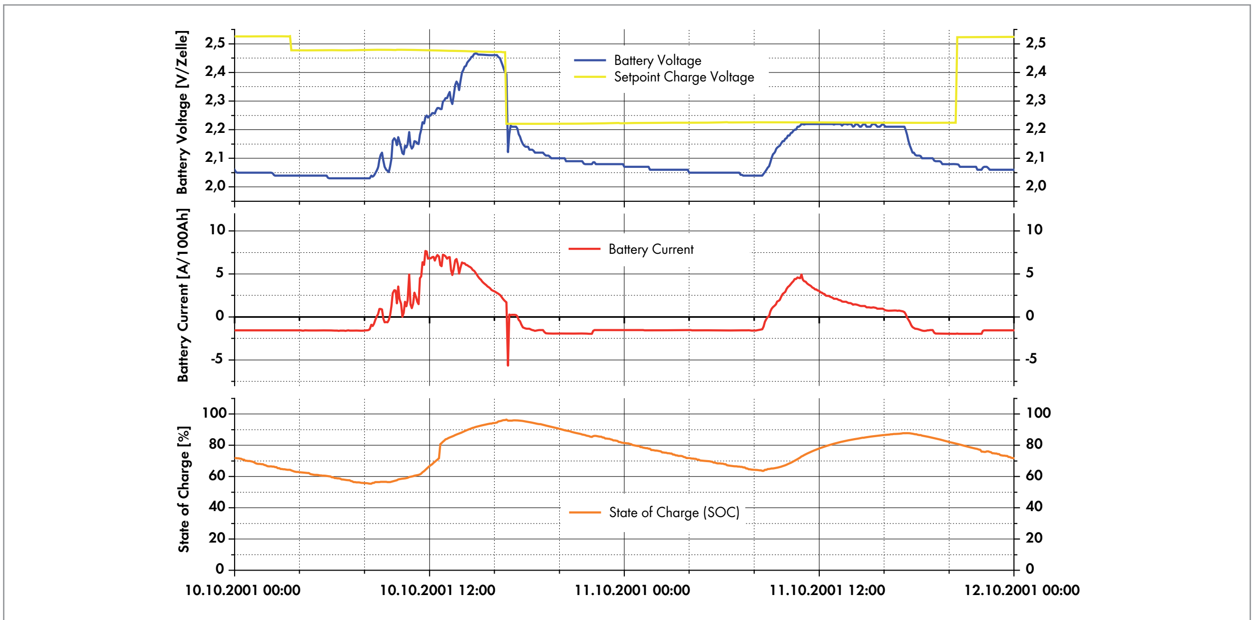


Fig. 4.4: Charge control and state of charge in a Greek hybrid PV system over a period of two days

4.2.1 Generator Management

The battery inverter generates a start or stop signal for a combustion genset based on the state of charge, or on the current power in conjunction with timer functions. In addition, it observes warm-up and minimum running times, as well as cool-down periods for the generator. This results in low-maintenance operation and a significant increase in the service life of the generator.

Fast, precise generator current control ensures that the generator is always maintained at the optimal operating point. Even in the case of sudden load changes, the Sunny Island battery inverter absorbs most of the load fluctuations and assists the generator by supplying power from the battery. As a result, even generators which are small in relation to the rated load can be safely used.

This process functions not only with diesel and gasoline generators, but also with small hydroelectric power plants (see Fig. 4.5). Here, the voltage fluctuations are attributable to the different reactive power situations within the system.

4.2.2 System Management

Hybrid systems supplying very dynamic loads (machines, household appliances, kitchen appliances) in addition to lighting, radios, TVs, and refrigerators, should not be controlled purely on the basis of energetic values such as state of charge. When the power demand is high, it does not necessarily need to be covered by the battery, but can be directly supplied from the connected generator. This significantly increases the system's efficiency and provides for a longer battery life as a result of a lower rate of energy flow through the battery. The option of starting up the generator at times of increased consumer demand is therefore most convenient. Load management allowing uncritical loads to be switched off temporarily also improves system performance. These and other functions can be activated in the Sunny Island. The battery inverter has a very high overload capacity which provides enough time to adjust to such situations and enables it to cope easily with, for instance, machine start-up currents.

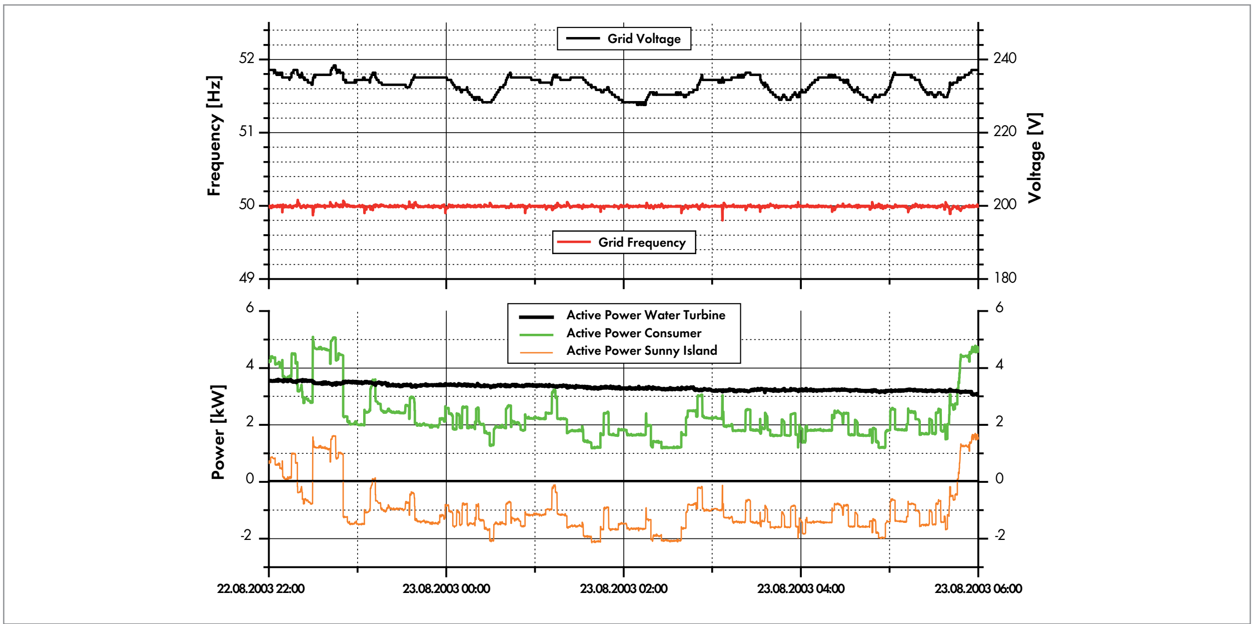


Fig. 4.5: Generator current control interacting with a water turbine

5. Communication in the Stand-Alone Power Grid

In stand-alone power systems communication equipment can be used for three different purposes, as follows:
1. Function-related communication
2. Supportive communication
3. General diagnostics

1. The system tasks can make a function-related communication necessary. For example, if several battery inverters are connected in parallel or operated in a three-phase stand-alone power grid, they will need to communicate with each other in order to exchange data or comply with electrical parameters such as phase shifts. No other communication tools are necessary.

2. Supportive communication serves to evaluate data so that optimum plant operation can be verified and controlled. For this purpose, communication with Sunny Island is usually sufficient, since the Sunny Island can simultaneously collect data from the batteries, external sources and loads. This data can be recorded and stored by a Sunny WebBox. To activate this function, the data logger is linked via an RS485 bus. If required, Sunny WebBox will send the data to Sunny Portal where it will be available online from anywhere in the world.

3. General diagnostics involves communication with practically every component in the system. Each individual device can be detected and the data recorded. Via a communication bus (such as RS485) you can link up a Sunny Island, Sunny Boy, Hydro Boy, Windy Boy or Smart Load to the Sunny WebBox. In this way, a detailed data analysis can be performed.

All communication tasks mentioned here can also be carried out locally with a laptop or PC. Software programs for such applications are available for download free of charge.

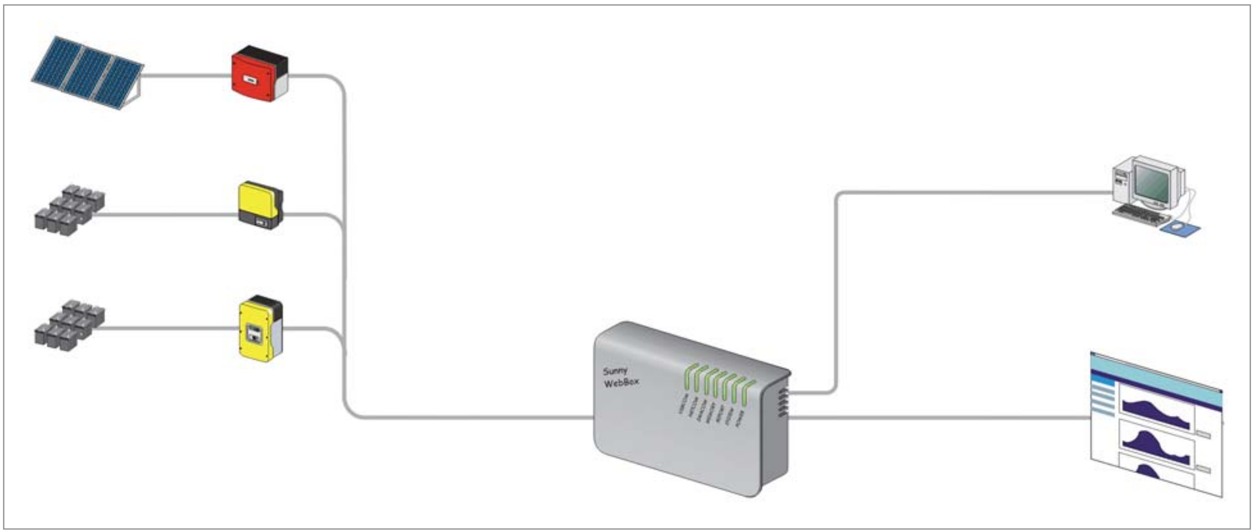


Fig. 5.1: Communication options in the stand-alone power grid

5.1 Sunny WebBox – the Communications Center

The Sunny WebBox is the link between the stand-alone system and the plant operator. Through its direct connection with the Sunny Portal via the Internet, this data logger opens up new possibilities for data collection, evaluation, and individual visualization on any PC using a standard web browser. From RS232 through RS485, the Sunny WebBox supports all existing communication channels to the SMA inverters. Data can be transmitted to the user via the Sunny Portal, and systems can be configured via the integrated Ethernet controller or over a telephone modem. The system data is stored in the WebBox on a removable flash memory card. This data can be automatically transmitted to the Sunny Portal via the Internet at configurable time intervals.

Overview of Sunny WebBox Features

- Continuous system monitoring
- Early detection of operation failures
- Recording of energy yields
- Diagnosis and plant configuration with any PC (Windows, Linux, Mac OS)
- Data preparation and graphical visualization free of charge in the Internet via Sunny Portal
- Monitoring of up to 50 inverters of various types per system
- Transportable data storage on removable MMC/SD card with practically no time constraints
- Low energy consumption

5.2 Sunny Portal – Online Data Storage and Display

With the free SMA Sunny Portal, the current operational data of a stand-alone power system can be recalled from anywhere in the world. Thus, operators are informed about the status of their power supply at all times. At the same time, it is possible to carry out reliable remote diagnostics via a secure Internet connection. In addition to displaying yields and power data, the WebService also enables status reports to be sent automatically by e-mail.

The completely pre-configured Sunny Portal is suitable not only for small stand-alone power grids, but also for large power supply systems. Data is permanently stored. Certain pages of the portal can be individually configured. The values of individual inverters or the plant as a whole can be displayed in an easy-to-read overview. To this end, attractive graphical representations such as bar charts, line or scatter diagrams are available.

Overview of Sunny Portal Features

- Simple remote monitoring from anywhere in the world
- Performance data displayed in charts and tables
- Free archiving of system data
- System information delivered by e-mail
- Creation of several web pages with visualizations of system data
- Individual page design based on HTML

The data transfer and system configuration are performed using an Ethernet connection or telephone with GSM modem. During this process, the data is automatically transferred at the transfer intervals that have been set.

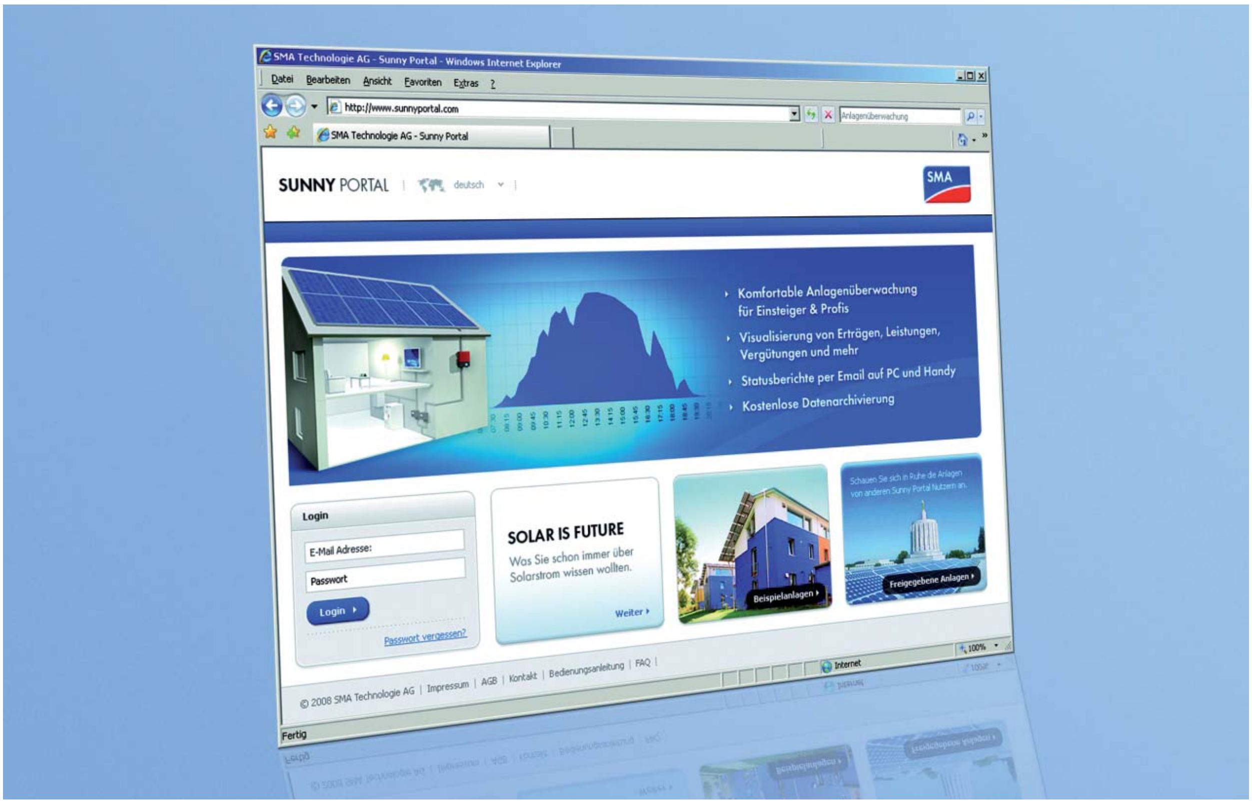


Fig. 5.2 Online data storage and display in Sunny Portal

6. Designing a Stand-Alone Power System

A professional system design, including dimensioning of PV generator and battery, is of prime importance for the efficiency and operational reliability of stand-alone power systems. It must take into account not only the energy consumption profile, but in particular the fluctuations in availability when using renewable power sources. The following examples of simulation software are available for the support of the plant designer: HYBRID2, PV SOL, PVS, and Anesys.

Designing the layout of a system is comparable to the work of an architect who must first draw up a plan of the house on paper before having it built. The design basically involves adapting a system to specific energetic and geographical conditions, as well as to the energy behavior of the system user.
These conditions are influenced by

- Solar fraction
- Autonomy time
- Energetic behavior
- Component manufacturer
- Geographical location

For an initial estimate of system size, necessary components and costs, a rough design can be accomplished in five steps. This gradual approach to the reality of a hybrid system helps to prevent the planner from unpleasant surprises.

6.1 Information on the Design Example

Since this is a rough design, the following points should be taken into consideration:

1. The five steps mentioned above comprise only an initial estimate
2. A full layout should include many more details, such as:
   - Seasonal fluctuations
   - Dimensioning oriented to the worst month
   - Prevailing irradiation conditions
   - Further individual specifications
3. Should you desire SMA's support in designing the plant, please complete the questionnaire with details of your Sunny Island System.
   This will serve:
   - to clarify technical details
   - as an aid to the Service-Team at a later date

6.2. Power Consumers and Hours of Use

The nominal power and power consumption of the loads play a fundamental role in a stand-alone power system. Table 6.1 shows an overview of standard loads, their nominal power, and typical operating times per day.

Power Consumers	Nominal Power [W]	Typical Operating [hr]	Energy [kWh]
Energy-saving lamp	15	2	0.03
Heating circulation pump	70	2	0.14
Water pump	200	3	0.6
Refrigerator	90	5	0.45
Freezer 200 l	100	5	0.5
Cooker (hob + oven)	2,300	0.75	1.7
Microwave	1,200	0.25	0.3
Electric kettle	1,800	0.25	0.45
Toaster	1,200	0.25	0.3
Mixer	200	0.25	0.05
Dishwasher	1,300	1	1.3
Vacuum cleaner	1,800	0.25	0.43
Iron	1,000	0.25	0.24
Sewing machine	80	0.25	0.02
Washing machine	2,000	1	2
Dryer	1,000	4	4
Radio	5	3	0.015
DVD player	15	2	0.03
Amplifier	100	2	0.2
TV (70 cm diagonal)	100	4	0.4
Satellite receiver	18	3	0.054
Video recorder	20	1	0.02
Computer	250	2	0.5
Thermal fax machine	10	0.25	0.0025
Laser printer	100	2	0.2
Air conditioner (room)	3,000	2	6
Hair dryer	1,000	0.25	0.25
Electric razor	15	2	0.03

Table 6.1: Overview of standard loads

6.3 Design Procedure

The more information about the stand-alone power system can be compiled, the more it will contribute to an optimum system design. In any case, the following questions from six different areas should be answered.

1. The areas of application of the planned system
- Is the system to serve as a stand-alone system or a grid-backup system?
- Is the system to be installed in single- or three-phase operation?

2. Geographic characteristics
- In which country is the system to be installed?
- What are the solar irradiation and temperature levels?
- What is the average wind speed on site?

3. Power generators
- Which power generators are to be used? PV, diesel, wind, water, or other?

4. Renewable fraction
- How high should the renewable fraction using renewable energies be (ratio e.g. of PV energy to diesel energy)?

5. Current consumption
- How much current is consumed per year or per day?

6. Power demand
- What is the peak power demand in a day?

On the basis of the data requested here, it is possible to compile an initial design which provides information on the scale, suitable power sources, and components of the plant.

6.4 Selection of the Stand-Alone Power Inverter

When selecting your device, it is important to remember that some stand-alone power inverters only operate on single-phase current, while others operate on three-phase current. A further factor to be considered is their differing power output range.

Sunny Island model designation key

In the model designation **SI XYZZ**:
X, Y = Continuous AC output [kW] at 25 °C
(e.g., **SI 2224** = 2.2 kW at 25 °C)
ZZ = DC battery voltage [V]

30-Minute Power	Single-Phase System	Three-Phase System
P_{max} = 1–2.7 kW	SI 2012	–
P_{max} = 1–2.9 kW	SI 2224	–
P_{max} = 1–8.7 kW	–	SI 2224 / SI 2012
P_{max} = 1–4.2 kW	SI 3324	–
P_{max} = 2–6.5 kW	SI 5048	–
P_{max} = 6–78 kW	–	SI 5048

Table 6.2: Selection of the stand-alone power inverters

Based on

a) the maximum power P_{max} and
b) the number of phases,

you can select the appropriate Sunny Island model:

Example Calculation 1

The number of stand-alone power inverters in **single-phase systems** with higher power outputs is determined by dividing the maximum power P_{max} by the 30-minute power of the Sunny Island model.

$$\frac{P_{max}}{6.5\ \text{kW}} = \text{number of SI 5048}$$

By rounding up the result to the next higher whole number, you will derive the number of Sunny Island devices needed.

$$P_{max} = 16\ \text{kW}$$

$$\frac{P_{max}}{6.5\ \text{kW}} = \text{number of SI 5048}$$

$$\frac{16\ \text{kW}}{6.5\ \text{kW}} = 2.5\ \text{devices} \approx 3 \times \text{SI 5048}$$

The number of devices in **three-phase systems** can also be determined on the basis of the 30-minute power of the Sunny Island. However, you will need to round up the result to the next higher number which is divisible by 3. This is the only way to distribute the inverters symmetrically across the phases:

$$P_{max} = 32\ \text{kW}$$

$$\frac{P_{max}}{6.5\ \text{kW}} = \text{number of SI 5048}$$

$$\frac{32\ \text{kW}}{6.5\ \text{kW}} = 4.9\ \text{devices} \approx 6\ \text{x SI 5048}$$

6.5 Dimensioning of the Battery

The size of the battery depends primarily on the:

- Autonomy time
- Annual energy demand (Ea)
- Average system efficiency during discharge (η = approximately 0.9)

Any time span appropriate to the application can be used for calculating the autonomy time. However, we recommend basing the dimensioning process on the empirical values found in the following Table 6.3.

	Autonomy Time (days)	Battery Type
Backup (Europe)	0.5	OGi
Backup (weak grid)	1	Cycle-proof OGi
PV or wind power system with a battery	4	OPzV
System with a diesel generator	2	OPzV
System with a water turbine	1.5	OPzV

Table 6.3: Autonomy times for various applications

Example Calculation 2

Depending on local conditions, the battery size is given either in kWh or Ah.

Please note: Batteries are not available in all sizes. Battery manufacturers offer standard sizes. Selection of the next larger standard size is recommended.

The battery voltage depends on the stand-alone power inverters used, as follows:
Sunny Island 2012: 12 V
Sunny Island 2224 and 3324: 24 V
Sunny Island 5048: 48 V

$$\text{Battery size [kWh]} = \frac{\text{autonomy time} \times \frac{Ea}{365}}{\eta}$$

$$\text{Battery size [Ah]} = \text{Battery size [kWh]} \times \frac{1{,}000}{\text{Battery voltage}}$$

System with a diesel generator
Autonomy time: 2 days
Annual energy consumption [Ea]: 4,500 kWh
Average system efficiency [η]: 0.9
Selected Sunny Island model: SI 2224

$$\text{Battery size [kWh]} = \frac{2\text{ days} \times \frac{4{,}500\text{ kWh}}{365}}{0.9} = 27.4\text{ kWh}$$

$$\text{Battery size [Ah]} = 27.4\text{ kWh} \times \frac{1{,}000}{24\text{ V}} = 1{,}140\text{ Ah}$$

6.6 Dimensioning of the PV System

The size of the PV system depends on:

- Annual energy demand
- System efficiency (η = approximately 0.7)[1]
- Solar fraction (SF)
- Solar irradiation

The region in which the system is to be installed needs to be established at a preliminary stage. The local level of solar irradiation and the appropriate solar fraction can vary considerably (see Table 6.4).

	Energy Yield E_{PV} per Year and kWp	**Appropriate Solar Fraction (SF)**
Germany	800–900 kWh	50–70 %
Southern Europe	1,300–1,450 kWh	60–90 %
North or South Africa	1,450–1,700 kWh	60–100 %
Saudi Arabia (extremely high)	1,800 kW	60–100 %

Table 6.4: Local solar irradiation levels and appropriate solar fraction

Example calculation 3

Using the above values, it is possible to calculate the approximate PV plant size in kWp for a single-family house in southern Europe.

$$P_{PV} = Ea \times \frac{1}{\eta_{sys}} \times \frac{SF}{E_{PV}}$$

Annual energy consumption [Ea]: 4,500 kWh
Average system efficiency [η_{sys}]: 0.7
Solar fraction [SF]: 70 %
Solar irradiation [E_{PV}]: 1,300 kWh

$$P_{PV} = 4{,}500 \text{ kWh} \times \frac{1}{0.7} \times \frac{70\ \%}{1{,}300 \text{ kWh}} = 3.46 \text{ kWp}$$

An exact design for the solar field and the solar inverter as well as the appropriate cabling can be calculated with the aid of the design tool SMA Sunny Design (http://www.sma.de/en/products/software/sunny-design.html).

[1] The system efficiency includes the charging and discharging efficiencies, power output losses, losses due to reactive power, etc.

6.7 Design of the Diesel Generator

Determining the size of a diesel generator is quite simple: Its nominal power should equal about 80 to 120 % of the Sunny Island's nominal power. However, it is preferable to keep the value below 100 %, since this means that the generator will be operating at optimum load. This ensures a long service life and also good diesel utilization.

6.8 Calculation of System Costs

On the basis of this rough design, an initial estimate of system costs can also take place. The costs in the calculation shown here include:

- cost of stand-alone power inverter
- cost of storage battery
- cost of PV system
- cost of diesel generator
- cost of assembly and installation

Any further items missing here will need to be included at a more detailed stage. Due to the wide range of system variants, they cannot be taken into consideration at this stage.

Summary of System Costs:

Cost of Sunny Island	device quantity × device price
Cost of battery	E_{bat} [kWh] × 200 – 300 €[2]
Cost of PV	P_{PV} [kWp] × 3,500 €[3]
Cost of diesel	P_{Diesel} × 1,000 €
Subtotal	xy €
Installation (15 %)	0.15 × subtotal
Total cost	xy €

[2] obtainable from battery manufacturer

[3] as per end 2009

7. Economic Aspects of Stand-Alone Power Systems

From an economic perspective, today stand-alone power systems with a storage battery are considerably more cost-effective in the kW power range than systems which use diesel generators only. Due to the longer service life and lower maintenance costs of the units, even larger hybrid systems which use a diesel generator solely to avoid long-term battery storage can be operated at lower costs than stations working exclusively with diesel units. In particular, any evaluation of the costs arising must make provision for the fact that in remote regions one kilowatt hour can easily cost between 0.50 and 1.50 Euro.

The investment costs for expanding a grid depend primarily on the length of the grid expansion. In the case of hybrid systems the investment costs depend on the types of loads to be supplied. The required size of the PV plant is derived from these factors.

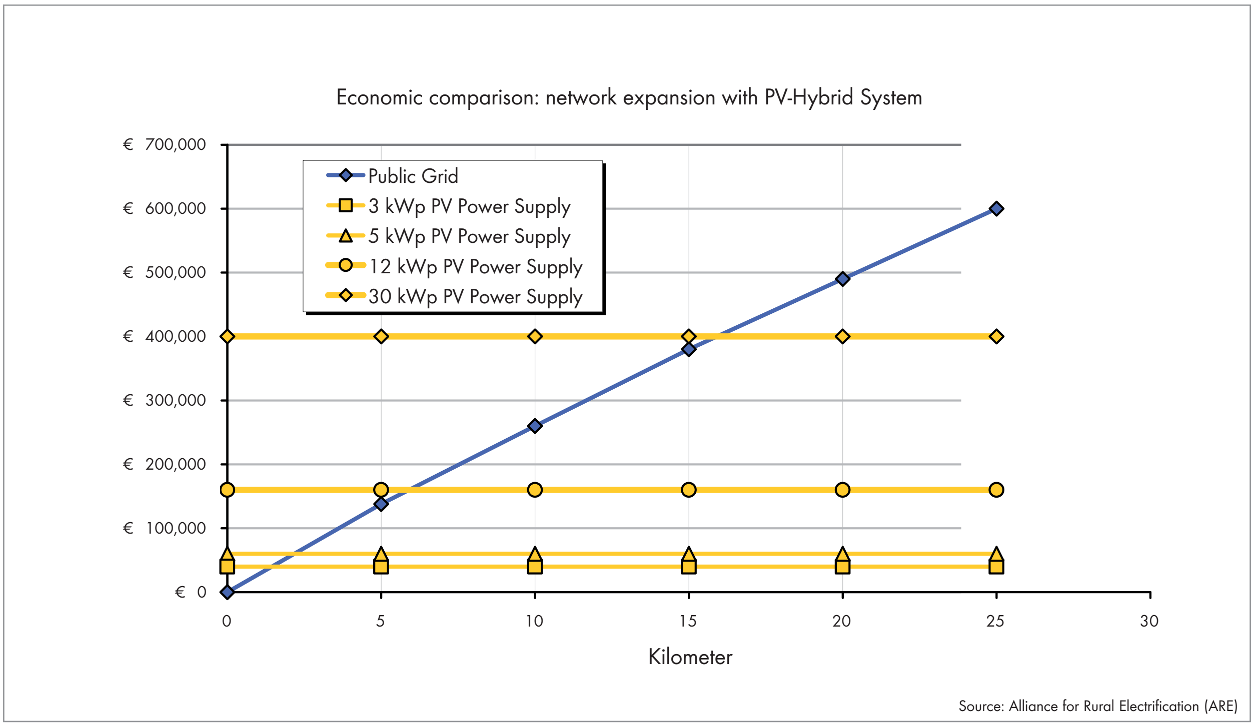


Fig. 7.1: Cost effectiveness of stand-alone applications as a function of the distance from the public grid

The cost-effectiveness of PV hybrid systems compared to pure diesel systems is clearly demonstrated if an examination of the costs is carried out over the service life of the two systems. From the example of an application in Tanzania (East Africa), it is shown that the higher initial investment cost of the PV hybrid system in comparison to a pure diesel power station is already recouped in the 6th year due to the substantially higher operational costs of a diesel generator. In the subsequent years, the advantages of using a PV hybrid system will continue to increase consistently.

Data for a diesel-powered system
Diesel generator 25 kVA

Data for a diesel-powered PV hybrid system:
25 kVA diesel generator
Photovoltaic plant 30 kWp
Stand-alone power Inverter 30 kW
Battery 240 kWh

PV hybrid systems can be operated economically on a long-term basis. In view of the rising cost of energy and raw materials, hybrid systems running on renewable energy sources present a real alternative and will open up new areas of application.

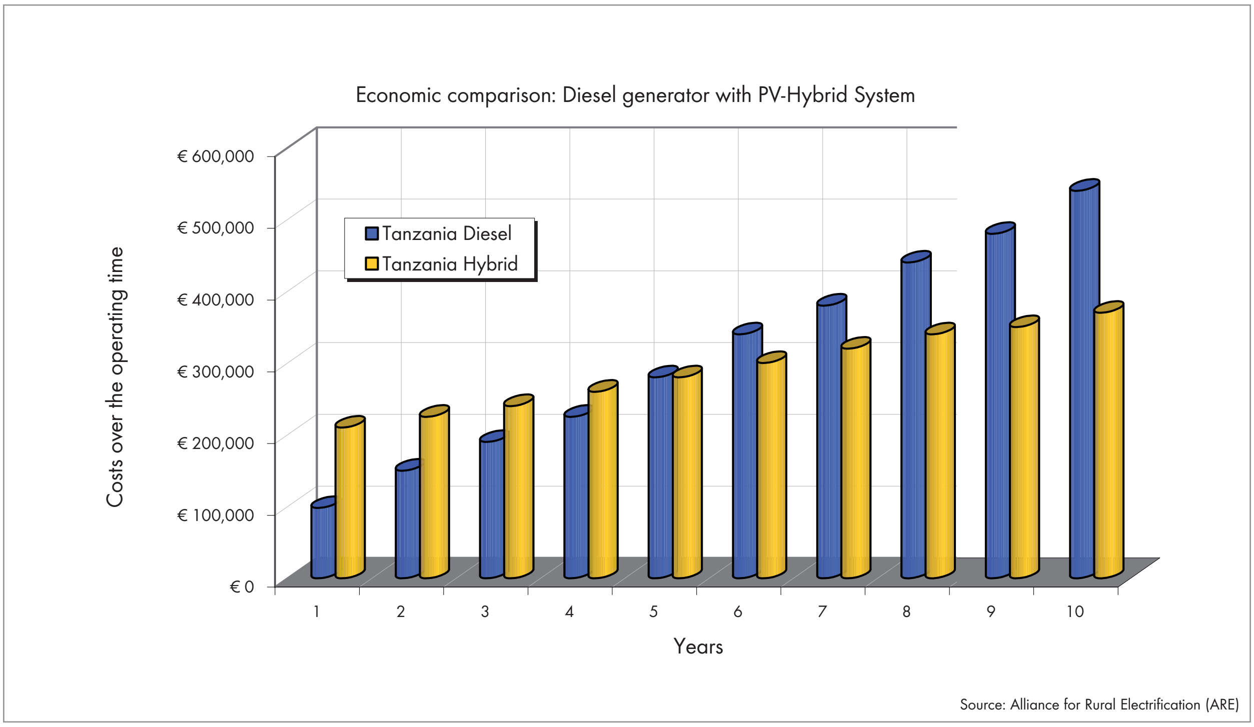


Fig. 7.2: Cost-effectiveness of stand-alone applications

8. Competent, Flexible, Worldwide: SMA Service

For 20 years, SMA has been developing and producing inverters for both grid-connected photovoltaic plants and decentralized power systems. These many years of experience provide the basis on which SMA continues to develop its products. Today, a broad selection of different stand-alone or battery inverters is available – both for large-scale stand-alone power grids and for emergency power systems. The devices are specifically designed for your particular application and guarantee optimal operation even under extremely unfavourable conditions.

A stable power supply requires not only long-lasting components, but also a reliable service partner. This is why SMA offers innovative, cutting-edge technology and comprehensive service as a one-stop solution. Whether it be the SMA's Serviceline, our on-site service, extensive warranty program, or post-service-life acceptance of devices, SMA's flexible service solutions are precisely tailored to the customer's needs.

The experts on the telephone Serviceline are supporting system operators in the planning, installation and commissioning of Sunny Island Systems, providing advice on technical queries and on system monitoring. The **Sunny Island customer service** is available **free of charge at telephone number +49 561 9522-399**.

With more than 20 Service Centers in Germany to date, and a well-developed international service infrastructure, SMA is always on the spot. Whatever your question, from installation or maintenance to system analysis, the SMA Serviceteam is a competent partner for all system operators.

SMA products are of the highest quality and come equipped with a standard five-year warranty. In addition, SMA offers an extended warranty, which entitles the system operator to free repairs or a replacement device for an additional 20 years.

9. References

With its Sunny Island product line, SMA is providing the necessary technology for the construction of modular stand-alone power grids. At SMA, system planners find a suitable device for every application, no matter whether it will be powering a village in China, a hospital in India, an Alpine hut in Italy, or a farm in Germany. With over 1,000 stand-alone systems installed throughout the world, SMA has great experience in the area of autonomous power supply – and also has individual solutions ready for challenging projects.

Fig. 9.1: Power supply for a house in Ghana (West Africa)

Fig. 9.2: An Alpine hut supplied with PV electricity

Fig. 9.3: In China, Sunny Island Systems supply electricity to entire villages

Fig. 9.4: In China, Sunny Island Systems supply electricity to entire villages

10. Literature

[1] Beverungen, S.: "Review of Energy Management Strategies for Hybrid Energy Systems", Internal Report of the University of Kassel, IEE-RE Efficient Energy Conversion; Kassel (2000)

[2] Sauer, D. U., et al.: „Entwicklung und Test von Ladestrategien für Gel- und Vliesbatterien in autonomen Systemen", Final Report of a Research Project, Fraunhofer ISE; Freiburg (2001)

[3] Bopp, G.; Bächler, M.; Wollny, M.; Jossen, A. et al.: „Systemkorrelierende Auswertung und Bewertung des Betriebsverhaltens in bestehenden PV-Anlagen", Final Report of a Research Project, ZSW; Ulm (1999)

[4] SMA Technologie AG: „Stromversorgung netzferner Gebiete", brochure; Niestetal (2007)

[5] SMA Technologie AG: „Sunny Island 5048 – Neuer Batteriewechselrichter für Inselanwendungen", brochure; Niestetal (2006)

[6] SMA Technologie AG: „Solarstrom auch bei Netzausfall", brochure; Niestetal (2007)

[7] Meinhardt, M.; Rothert, M.; Engler, A.: "New V/f-Statics controlled Battery Inverter: Sunny Island"; Niestetal (2003)

[8] Wollny, M.: "Electrifying China"; offprint Refocus – "Renewable energy focus", Oxford (2005)

[9] Cramer, G.; Ibrahim, M.; Kleinkauf, W.: "PV System Technologies"; offprint Refocus – "Renewable energy focus", Oxford (2004)

[10] Rothert, M.; Wollny, M.: "Optimized Operation Management in Hybrid Systems"; Niestetal (2006)

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