During the past decade, renewable energy technologies have achieved very high engineering standards, not only due to ecological reasons but also because of the decentralised nature of renewable resources which makes them able to contribute to solving the above mentioned electrification problems. Taking PV system technologies as one example that stands for renewable energy technology as a whole, this article points out existing possibilities of integrating PV systems into both the available and the planned power supply structures that are also suitable for electrification of remote areas.

**Decentralised power systems**
Up until today, electricity consumers have predominantly been served by remote central power stations through long transmission and distribution grids. These utility grids provide the end-user with AC power of a relatively fixed frequency and voltage (e.g. 230/400 V of 50 Hz). The continuous increase of electricity consumption overloads power stations and distribution grids which influences the supply security and the power quality. Conceptually, these central generation supply infrastructures can be complemented by decentralised generation systems for combined heat and power production. These decentralised power supply systems are characterised by relatively small generation units located nearby the consumers and they effectively use the locally available energy resources. Consequently, generation and consumption processes take place locally [1]. That enhances the usability of electrical and heat energy and the exploitation of local energy potentials (especially renewable energies such as solar, wind, biomass and hydropower). Additionally, energy losses which occur due to voltage level conversion and long power transmission and distribution lines are minimised. Accordingly, the overall efficiency is increased, the economic situation of the region is improved and the conditions of sustainability are fulfilled.

The distributed nature of renewable energies perfectly matches this decentralised supply strategy. Depending on regional conditions, the decentralisation concept can be fulfilled either by connecting a PV power plant (in the kW to MW range) to suitable points of the utility grids or by installing stand-alone systems and island grids in order to supply off-grid consumers [2]. Accordingly, the decentralised PV system configurations used to supply AC power can be classified as follows:
- PV in utility grids:
  - Only PV
  - PV with battery storage
- PV in off-grid applications
  - PV battery systems
  - PV hybrid systems

**Figure 1: Modular and AC-compatible hybrid system technology with standardised modules, including the possibilities of supplying single consumers or forming island grids and feeding into the utility grid**

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All these supply configurations are shown in Figure 1 and can be modularly structured. The grid connected structure is the dominant PV application area in industrialised countries such as Europe, Japan and the USA. If the PV plant is equipped with the suitable power conditioning unit it can supply power to the utility grid, as shown on the right hand side of Figure 1. Integrating the PV plant with storage media (usually a battery) improves the energy supply availability of weak grids (back-up function). In PV applications for island grids used to supply remote and off-grid consumers, the PV plant is integrated with battery storage in order to ensure the desired availability. For larger-scale applications the PV plant can also be combined with other energy converters (e.g. wind energy converters and diesel generators) and storage units to form hybrid power supply systems, as shown in Figure 1.

Until now, the lead acid battery with its different technologies is the dominant storage medium in off-grid PV systems. Due to its high costs (about 100 €/kWh), a battery is applied for short- and medium-term energy buffering [3]. Additionally, auxiliary generators, driven by diesel engines or microturbines, are used as back-up units in order to improve the supply security of these PV stand-alone systems. In the future, fuel cells are also of increasing interest as back-up units, since they generate power more controllably and reduce greenhouse gases.

**Grid connected PV systems**

PV plants in grid connected applications are tied to the grid via power conditioning units (inverters) of several technological concepts. These inverters play a key role in the energy efficiency and reliability since they operate the PV array at the Maximum Power Point (MPP). Moreover, inverters convert the DC power generated by PV modules into alternating current (AC) of the desired voltage and frequency (e.g. 230 V/ 50 Hz). The basic inverter technologies for PV grid-tied structures are classified as follows:

- **Central inverters**: in this topology the PV plant (> 10 kW) is arranged in many parallel strings that are connected to a single central inverter on the DC-side (Figure 2a). These inverters are characterised by high efficiency and the lowest specific cost. However, the energy yield of the PV plant decreases due to module mismatching and partial shading conditions. Also, the reliability of the plant is limited due to the dependence of power generation on a single component: the failure of the central inverter results in the whole PV plant being out of operation.

- **String inverter**: similar to the central inverter, the PV plant in this concept is divided into several parallel strings as shown in Figure 2b. Each of the PV strings is assigned to a designated inverter, the so-called “string inverter”. String inverters have the capability of separate MPP tracking of each PV string. This increases the energy yield via the reduction of mismatching and partial shading losses. These superior technical characteristics lead to a reduction in the system cost, increase the energy yield and enhance the supply reliability. String inverters, like the “Sunny Boy” range, have evolved as a standard in PV system technology for grid coupling of PV plants.

- **Multi-string inverter**: this concept is an evolution of string technology with a higher nominal power. Multi-string inverter technology allows the connection of several strings with separate MPP tracking systems (via DC/DC converter) to a common power conditioning unit (DC/AC inverter). Accordingly, a compact and cost-effective solution which combines the advantages of central and string technologies is achieved. This multi-string topology allows the integration of PV strings of different technologies and of various orientations (south, west and east). These...
characteristics allow time shifted solar power which optimise the operation efficiencies of each string separately. The application area of the multi-string inverter cover PV plants of 3-10 kW.

Modular integrated inverter: one inverter is used for each module (Figure 2c). This topology optimises the adaptability of the inverter to the PV characteristics, since each module has its own MPP tracker. Although the module integrated inverter optimises the energy yield, it has a lower efficiency than the string inverter. Module integrated inverters are characterised by more extended AC-side cabling, since each module of the PV plant has to be connected to the available AC grid (e.g. 230 V/ 50 Hz). Also, the maintenance processes are quite complicated, especially for facade-integrated PV systems. This concept can be implemented for PV plants of about 50-400 W peak.

These three types of inverters are available on the market, and their implementation depends on the technical feasibility to select the most appropriate inverter topology.

Cost development
In addition to the PV module cost, the cost and reliability of PV inverters are basic issues if market competitive PV supply systems are the aim. The inverter cost share represents about 10-15% of the total investment cost of a grid connected system. In Figure 3 the development of the PV inverters specific cost ($/W_{AC}$) of small to medium power range (1-10 kW) is illustrated. In this figure it can be seen that the inverter cost of this power class has decreased by more than 50% during the last decade. The main reasons for this reduction are the increase of the production quantities and the implementation of new system technologies (e.g. string-inverters). A further 50% reduction of the specific cost is anticipated during the coming decade. The corresponding specific cost is expected to achieve about 0.3 $/W_{AC}$ by the year 2010, which requires the implementation of specific measures for the development and the manufacturing processes.

Stand-alone and island grid applications
Stand-alone and island grid systems are those PV power generation plants which are not connected to utility grids. The island grid systems can be classified according to the voltage (DC or AC) they are coupled with. An overview of the market available system concepts is described as follows:

Solar-Home-Systems (SHS): all consumers and generators are coupled on the DC voltage level exclusively (Figure 4). Today, several hundred thousand SHSs, in the power range of about 200 W, have been installed mainly in rural areas of Asia, Africa and South America. Supported by an additional small inverter, the consumer can use the DC-system to supply any standardised AC load.

Small AC local grid with DC-coupled components: this technology emerged due to the need to supply (medium power) AC loads by DC power sources and to charge the battery on the DC-side also via combustion generators like diesel gensets (Figure 5). Such a configuration is used to supply remote or rural consumers of bigger energy demand than the SHS (e.g. cottages, small workshops and farms). The common power range is between 1 and 5 kW and the DC-voltage range is between 12 and 48 V.

Modular AC-coupled systems: more flexible systems with modularly structured components are achieved by coupling all consumers and generators on the AC-side (Figure 6). Nowadays, this technology is commonly used in the power range above several kWs. According to the application type and energy resources availability, different renewable and conventional energy converters are also suitable to be added to the system to form a hybrid energy system. Since all converters, storage and back-up units of the decentralised systems can generate AC power of grid compatible charac-

![Figure 3: Development and prognosis of specific cost and production quantity for the PV inverter of nominal powers between 1 and 10 kW during two decades (\(^\text{\$} / W_{\text{AC}}\) indicates specific prices of products on the market)](image)

![Figure 4: Solar-Home-System with possibility of AC generation](image)

![Figure 5: Small AC power supply system with DC-coupled components](image)
teristics, they are also suitable to be connected to the utility grid. Moreover, this supply structure can be simply expanded by integrating further components or generators in order to cover the rising energy demand. Such structures are used to supply any electrical consumer, especially rural villages of developing and threshold countries where electricity, water pumping and water disinfection are basic needs.

The modular, AC-coupled PV system technologies have been developed for the first time by the Institute of Solar Energy Supply Technology (ISET e.V., Uni. Kassel) and the company SMA Regelsysteme GmbH. This concept has a huge market potential, especially in countries that lack appropriate conditions for utility grid extension. The power range of these island grid systems varies between 3-100 kW and can be realised in both single- and three-phase structures. As mentioned above, the modular technology has come up with very many advantages in simplifying the system engineering (design, installation, expansion and compatibility) and consequently minimises the specific system cost. Figure 7 shows an electrification strategy based on the modular AC-coupled PV hybrid system concept. This electrification and expansion strategy is summarised in the following steps: No electricity supply; Small PV/battery system (AC-coupled); Enlarged PV/battery system (AC-coupled); Hybrid system by integration of a Diesel generator; Implementation of further distributed PV systems and a wind turbine (all AC-coupled); Connection of a further village and grid extension.

The structure of such supply systems requires, in addition to the power conditioning equipment, a control and supervision unit which is responsible for implementing a specific operation control strategy and for securing the grid and system components [4]. In small and medium power systems (3-30 kW) this control unit is often integrated into the key component “battery bi-directional inverter” which simplifies system operation and decreases the investment costs. Figure 8 illustrates a prototype hybrid system which is developed and realised according to the modular system technology concept.

From the economic point of view, stand-alone systems and small off-grid plants (with battery storage) in the kW range are definitely more cost-effective than systems using solely diesel generators. Even larger PV hybrid systems (5 - 30 kW) using diesel generator sets only to avoid large long-term battery storage can operate at lower cost than purely diesel powered systems. This can be attributed to the high life cycle costs of the diesel generator set. For comparison, the kWh generated by diesel generator sets (10-30 kW) costs about 0.4-1.0 €/kWh.

PV power systems: the next generation

Modern decentralised power supply structures are expected to include several types of grids that operate in parallel to each other and communicate with service centres for control, supervision and remote maintenance purposes. Figure 9 shows how decentralised PV power systems will evolve to include: local (e.g. supply of single loads via stand-alone systems); regional (e.g. supply of amenities, businesses etc. via island grids); and trans-regional (coupling to utility grids) supply. These types of grids form supply structures which can be expanded step by step as the demand for electricity increases. A broad expansion of the

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**Diagram 1:** Expandable modularly structured hybrid plant with AC-coupled components

**Diagram 2:** AC-coupled hybrid system extending with increasing electricity demand
decentralised electrification would automatically lead to the interconnection of local grids to form regional or trans-regional grids. In such decentralised structures, communication is a key issue for security and cost-effective remote supervision and maintenance. In addition to the power-line coupling of the different system components and plants, another communication structure for control and supervision purposes is an essential feature for decentralised power supply structures. Each structure has to be equipped with the suitable communication technology, as shown by the dotted line in Figure 9. Hence, the application of modern communication technologies must influence the design of supply components and systems.

These decentralised power supply structures are anticipated to represent the future trend towards sustainable energy generation and to be the most effective solution for electrifying remote and rural areas. Moreover, the trend towards decentralised power structures (virtual power station) has also spread to industrialised countries. Price reduction as shown in Figure 3 is expected to be accomplished for other electronic components as well, such as charge regulators for small PV systems, AC/AC converters and for control and monitoring facilities of widely distributed systems. Especially, modular and AC-coupled PV plants and hybrid systems for decentralised electrification offer cost-effective energy supply comparable with systems that use conventional gensets only.

**Conclusion**

This article has described the trend towards decentralised energy supply structures with modular PV components. Moreover, the state-of-the-art in PV inverter technologies and their characteristics have been introduced. Among several application areas and system configurations, the modular AC coupled hybrid systems are considered to be an optimal solution for expandable and grid compatible power supply structures. An electrification and expansion strategy based on decentralised AC compatible PV hybrid systems has been introduced. Moreover, communication facilities are considered to be a key technology for control, supervision and remote maintenance of decentralised PV systems. Increasing the mass production of PV components and systems in the near future will lead to further cost reduction. Therefore, there is a need for innovative solutions for the development processes on both components and systems level.

**References**


