# RESEARCH ISSUES ON STAND-ALONE PV/HYBRID SYSTEMS: STATE-OF-ART AND FUTURE TECHNOLOGY PERSPECTIVES FOR THE INTEGRATION OF $\mu$ GRID TOPOLOGIES ON LOCAL ISLAND GRIDS

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## ABSTRACT

A review of the state-of-art on stand-alone PV/hybrid is presented in this paper. Gathered data on operational experiences of autonomous power stations on Hellenic islands show that energy production costs using conventional power supply sources is high and PV systems is a sustainable solution for electrification of distant areas. Emphasis is put on µGrid systems as these topologies have certain technical and economical advantages. The main characteristics of the µGrid facility on the island of Kythnos are analysed and new marketing concepts such are the value of PV electricity and the provision of ancillary services by renewables are reviewed. Research issues for stand-alone systems technology to be addressed on the short to medium term and medium to long term timescales are listed. These research priorities have been identified due to the existing knowledge of on-going research projects and the work under way by the expert groups of two European Technology Platforms.

# BACKGROUND

Off-grid or stand-alone systems are usually divided into professional applications, e.g. telecommunications, lighthouses, remote sensing and rural development applications such as, water pumping, street lighting, solar home systems (SHS) etc. The power rating of such applications typically varies from a few hundreds of Wp to 10kWp.

The so-called "central" stand-alone PV/hybrid systems are those designed to electrify isolated communities such as a small village or networks of houses usually located on islands or simply at a distance from the nearest electric network. The power range of such systems is typically between a few tenths of kWp to 100kWp, although higher capacity PV/hybrid stations have been built and operated during the last decade. A schematic of a PV/hybrid stand-alone system is presented in Figure 1 below.



Fig. 1 Typical layout of a stand-alone PV/hybrid system

Since the beginning of this century, the research community has been studying the technical advantages of the so-called micro-grids ( $\mu$ Grids) and their effectiveness in providing higher quality and more reliable power supply in the place of traditional "central" stand-alone systems as described above. In this way,  $\mu$ Grids can be considered as a type of stand-alone system, which additionally includes the possibility for grid connection when this becomes available.

The wide variation in system applications does not allow determination of definitive values for system costs at this stage. The PV generator is usually the most costly component in the system, typically accounting for 50% in stand-alone and 70% in grid-connected of the costs at system level. These values could vary considerably with application and system size, since the relative impact of the BoS and installation costs may vary substantially.

## **ELECTRICITY GENERATION ON ISLANDS**

The study analytically presented in [1], gives a comprehensive overview on power supply issues and electricity generation costs from diesel-based power stations on autonomous islands in Greece, Italy and France. The data of [1] refer to 1991 to 1994 values and an updated situation on the Greek islands with recent values is presented in this paper.

In Figures 1 and 2, the installed generation capacity on islands of up to 10,000 permanent inhabitants were taken from the Public Power Corporation (PPC) annual report and refer to year 2001.



Fig. 2 Specific installed on small autonomous Greek islands

As it is noticed in Fig. 1, on islands specific capacity varies from 3kW to 1kW per permanent resident. This is a high value compared to central power production. In Greece, the installed capacity of the mainland power production is less than 1kW per inhabitant. The large value of installed capacity per inhabitant on the islands is due to the difference in energy consumption between winter and summer seasons, as a result of the seasonal tourist activity.



Fig. 3 Energy production cost on small autonomous Greek islands

From Fig. 2 is seen that electricity production costs are strongly affected by the installed power capacity. The trend is that the annual average energy production cost decreases as the installed generating capacity in the islands increases. The cost of electricity production can be as high as 1 Euro/kWh while, on small to medium size islands, costs usually vary between 40 Eurocent and €20 Eurocent per kWh. Even on bigger islands, costs are rarely below 10 Eurocent/kWh.

The breakeven point for PV systems to become costeffective is for an island size between 500 and 1000 with inhabitants. This varies respect to local macroeconomic factors and the level of diesel generation units utilisation as a factor of the activities on an island during a typical year. On the other hand, load demand on small and medium size islands increased at an average rate of 8.5% per year over the last 15 years. Thus, the potential to integrate PV technology as a supportive power supply resource is high and has to be thoroughly considered by the system operator.

With these prices, electricity production from PV is already cost competitive. In Fig. 4, the electricity production costs on islands are compared with the corresponding costs of the mainland grid as presented by [2].



Fig. 4 Electricity generating cost for PV: utility prices at central stations and on islands

In Figure 4, the green area represents PV generation costs and is formed by the corresponding costs in central Europe (upper curve, average 900 sunshine hours per year), and in south Europe (lower curve, average 1800 sunshine hours per year). The red area and the blue areas indicate cost variations of utility peak power and bulk power respectively. The yellow lines have been integrated in Fig. 4 and form a new shaded area which represents average bulk power electricity production costs on a medium size island.

# **MICRO-GRID TOPOLOGIES**

Micro-grids ( $\mu$ Grids) are generally defined as low voltage networks with DG sources, together with local storage devices and controllable loads. Typically, the total installed capacity of a  $\mu$ Grid is in the range of a few hundred kWp to MWp.

A characteristic feature of  $\mu$ Grids is that although they usually operate connected to the distribution network, they can be automatically transferred to islanded mode, in case of faults in the upstream network and can be synchronised after restoration of the upstream network voltage. Microgrids can also operate autonomously, making them a type of stand-alone systems.

A typical layout of a micro-grid is presented in Figure 5 and includes several Distributed Generation (DG) power supply units and storage components at the low voltage side and the appropriate central controller for connection to the medium voltage grid.



Fig. 5 Schematic diagram of a µGrid topology

As it is seen in Figure 5, micro-generation includes relatively small size RES units, such as PV and wind, micro-turbines and fuel cells, CHP units and storage components such as flywheels and batteries. Renewable energy sources are intermittent, while micro-turbine and CHP units operation is usually thermally driven and electricity produced from such devices is considered as a by-product.

Presently, advanced knowledge to control and monitor such power generation units from a central point does not exist. As a result, there is little technical capability to coordinate effectively the operation of  $\mu$ Grids and exploit their advantages over conventional generation methodologies.

The utilisation of storage, both electrical and thermal, could assist to improve the controllability and economic operation of micro-generation units. Yet, advanced electrical storage systems have not been developed and if any, they usually serve for reliability issues. Finally, the use of Energy Management Systems is very limited and usually based on proprietary solutions. It is envisaged that in the foreseeable future, operation of utility systems will be shared between central and distributed generators. Control of DGs could be aggregated to form  $\mu$ Grids or "virtual power plants" to facilitate their integration both in the physical system and in the market.

The advantages of micro-grids are summarised as follows:

## Technical

- Energy production from PV or hybrid systems can be done centrally or even on an individual basis.
- Storage is central and energy management although complicated, is eventually more effective for the endusers.
- µGrid systems can be easily integrated to the main distribution network when available, with little or none modifications in the system design and the hardware components.
- Back-up power from diesel or other technologies is central and more efficient.

# **Economical**

- A µGrid system of a particular power and storage capacity is less costly compared to equal total capacity of individual stand-alone systems.
- Energy management and trading with the main grid is more straightforward, ancillary services can be better implemented.

# The µGrid Facility on Kythnos Island, Greece

Kythnos is a small island of some 1540 permanent inhabitants, belonging in the complex of Cyclades in the Aegean Sea. A  $\mu$ Grid field testing facility was installed in 1999 at the site Gaidouromantra, a small valley at the waterfront, see Fig. 6.



Fig. 6 Overview of the  $\mu\text{Grid}$  system on the island of Kythnos

The  $\mu$ Grid system electrifies a settlement of 12 houses which are approximately 4km away from the closest MV line of the island and operates at 230Vac in single phase mode. The components of the system are:

- 5 PV systems of total power 12kWp.
- A central battery bank of 80kWh total capacity.
- A diesel backup of 9kVA.
- 3 battery inverters, each 3.6kW maximum power output.

Advanced monitoring and the communication hardware have been installed to monitor the main operational parameters and extract useful results on  $\mu$ Grid system operation, see [3].

The grid and safety specifications for the house connections fulfil the technical requirements of PPC, which is the utility company. In this way, a future connection of the  $\mu$ Grid system with the island's MV lines will be feasible with little modifications on the existing layout and the characteristics of the components.

The battery inverters operate in a multi-master configuration. In this way, automatic load sharing is achieved through the utilisation of active power/frequency droop curves in the inverters control systems. The operation in frequency droop mode gives the technical possibility to switch load controllers in case that the battery SOC is sensed low or limit the power output of the PV inverters when the battery bank is full by increasing the grid frequency to 51.5 Hz.

At the point of connection to the µgrid, each house is equipped with a so-called Distributed Intelligent Load Controller (DILC). These controllers operate in the frequency mode. In the case of low battery SOC or system overload by the users, the controller will automatically disconnect a house when frequency drops below a threshold point, usually set at 49.14 Hz. After a shutdown, the battery inverter mimics the effect of an overloaded generator which is slowing down thus, effectively decreasing the µgrid frequency. Reconnection of a house to the µgrid is done via the DILC devices, progressively to avoid overloading.

New technical advancements in the  $\mu$ grid facility at Kythnos are now under way. These include partial load management in each house by intelligent controllers and an additional power supply source by a rated 5kW wind turbine.

# **New Energy Marketing Concepts**

# Value of PV Electricity

This seems to become an important issue that will be thoroughly assessed by the researchers. Addressing the concept of the "Value of PV Electricity" one implies that grid-connected PV systems as well as,  $\mu$ Grid topologies could be treated as ancillary service providers.

On the other hand, to be considered as a reliable provider and bearing in mind that PV is an intermittent power supply resource, one would need storage. Thus, intense research efforts need to be undertaken in order storage to be totally integrated as a system component which in combination with PV power supply can provide additional services to the grid.

Finally, with today's PV systems prices, a reasonable "kWh cost" figure in the lifetime of a solar electrification system can be reached only by assessing the technical possibilities of PV technology to considerably contribute to ancillary services required by the utilities, on top of the energy production on a year-round basis.

## Ancillary Services

Ancillary Services (AS), are technical services required for a satisfactory operation of an interconnected system. According to the EC co-funded project EU-DEEP, [4], the ancillary services required for a satisfactory operation of the interconnected system are (in bold fonts those more suited to  $\mu$ Grids):

- Energy Imbalance Service: energy correction for any hourly mismatch between a transmission customer's energy supply and the demand served.
- **Spinning Reserve Service:** additional capacity from electricity generators that are on-line, loaded to less than their maximum output, and available to serve customer demand immediately should a contingency occur.
- Supplemental Reserve Service: additional capacity from electricity generators that can be used to respond to a contingency within a short period, usually ten minutes.
- Reactive Supply and Voltage Control from Generating Sources Service: provides reactive supply through changes to generator reactive output to maintain transmission line voltage and facilitate electricity transfers.
- Regulation and Frequency Response Service: follow-up moment-to-moment variations in the demand or supply in a Control Area and maintaining scheduled interconnection power exchange.
- Scheduling, System Control and Dispatch Service: includes confirmation and implementation of interchange schedule with other Control Areas, transmission service, and ensuring operational security during the interchange transaction.
- Black start: grid restoration following a blackout.

As explained in [5], for both a reliable and secure operation, electric power systems require AS which mainly concern the supply (or consumption) of active or reactive power when it is needed for specific purposes and with certain time responses.

# **RESEARCH ISSUES FOR STAND-ALONE SYSTEMS**

As shown above, stand-alone PV systems can be implemented in a wide range of applications, sizes and situations and to meet a wide range of power needs. The European PV Technology Platform, [6], is now developing an updated research agenda based on input from expert groups from the European PV community.

The main topics under discussion refer to reduced component and system costs, increased system performance and lifetime and exploitation of the added value of the produced electricity by improving the services provided to the system operator.

The list below provides a summary of short to medium term research issues for stand-alone systems in the timescale 2008–2015:

- Development of power electronic components for stand-alone systems: emphasis on compatibility of components, new inverters optimised for different PV module technologies, development of low cost, highly efficient hardware for PV/hybrid systems, etc.
- Improve BoS components reliability and lifetime: emphasis on inverters and battery storage. For professional stand-alone systems BoS component lifetime should reach 20 years. For stand-alone systems in development applications, battery lifetime should increase to around 10 years.
- Development and testing of new storage technologies: the storage component should be treated as an integrated part in a system.
- Battery Management Systems: on the system level, adapted for the new generation of batteries.
- Decrease costs of BoS: target 1.2 Euro/Wp by 2010.
- Management of µGrids: emphasis on island grids with high share of PV generators, control and grid stability issues, voltage and frequency regulation, harmonics.
- Advancements in DG systems: development of new analytical tools and simulation methods for power system studies, billing and metering of off-grid systems.
- Value of PV electricity: assessment of kWh cost on the lifetime basis, load matching and storage options, bearing in mind that electricity production by PV/µGrid systems strongly depends on local circumstances.
- Development of standards: on performance, energy rating and safety issues. Also, standards regarding the connection of decentralised power systems to the grid need to be developed.
- Control and monitoring of system output: new low-cost options and advanced measuring devices and protocols.
- Cost reduction of ready for commercialisation systems: street lighting systems are still far too costly for an effective market penetration.

Research issues on the medium to long term timescale 2015 to 2025 include:

- Innovative storage technologies: low capacity storage 1–10 kWh, high capacity storage >1MWh.
- Storage integrated on PV module: aim is to extend lifetime of the system level.
- Alternative storage technologies: e.g. H<sub>2</sub>.
- Mass production of equipment: development of specific machinery.
- Quality assurance: improved methodologies and development and adaptation of guidelines.
- Harmonisation of stand-alone system component reliability: aim is the increased overall system lifetime.
- Pilot plant development and assessment of new concepts: advanced µGrids, virtual power plans, active houses, effective contribution of DG to ancillary services, the role of storage in a power system design, reliability of power systems with high DG penetration, etc.
- Decrease costs of BoS: target 0.7 Euro/Wp by 2025.
- Recycling: development of advanced recycling processes for thin-film modules and BoS components.

# CONCLUSIONS

Even with present prices, PV technology is competitive to conventional power generation on small and medium size autonomous islands. Indicative cases in Greece have shown that average kWh electricity production costs vary between 0.2 Eurocent and 0.4 Eurocent. However, in order to meet the cost targets required for a high penetration of PV technology into the energy supply market in the 2020–2030 time period, substantial and consistent system level cost reductions must be made alongside those for the PV module.

A transition period from traditional stand-alone systems to  $\mu$ Grid topologies is already under way. Micro-grids have certain technical and economical advantages over typical stand-alone systems. Operational experiences from the  $\mu$ Grid test field on the island of Kythnos have shown that effective and reliable control of the individual components and energy management issues are essential research priorities that have to be tackled.

Intensive research on new storage technologies is needed for an efficient integration of PV/hybrid systems and  $\mu$ Grids into power supply networks of the future. Further research on the true value of PV electricity has to be undertaken, especially via the contributions of DG to ancillary services required by the utilities.

Additional research priorities on the short to medium term timescale include quality assurance issues, development of standards and extension of lifetime of the components of PV systems.

## ACKNOWLEDGEMENTS

This paper was presented in the 4<sup>th</sup> WCPEC due to the financial support of EC project PV-ERA-NET, contract No ERAC-2004-011814, which has main scope the networking and integration of National and Regional RTD programmes in the field of PV technology.

Specific parts of the section on research issues for standalone systems have been identified in the work undertaken by experts in the field within the two Technology Platforms for PV, see [6], and Electricity Networks of the Future, both now under way.

Many thanks are due to the Conference organisers and to Prof. Nicola Pearsall of the Northumbria University, PV Applications Centre, UK, for the invitation to present this work in this meeting.

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