TECHNOLOGICAL EDUCATION INSTITUTE OF PIRAEUS — LAB OF SOFT ENERGY APPLICATIONS & ENVIRONMENTAL PROTECTION — DEPT. OF MECHANICAL ENGINEERING

OFF-GRID SOLUTIONS BASED ON RES AND ENERGY STORAGE CONFIGURATIONS

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1. PROBLEM DESCRIPTION

- Energy and especially electricity is a vital element of contemporary societies, like fresh water and clean air;

However,

- United Nations estimate that almost two billion people have no direct access to electrical networks.

- Autonomous stand-alone systems could prove a very promising solution for the electrification of remote areas.

PROBLEM DESCRIPTION (cont.)

- In Greece, due to its geographical structure, several thousands of remote consumers exist, located on the numerous islands scattered throughout the Aegean and Ionian Archipelagos, as well as in rural areas of mainland, i.e. country houses, shelters, telecommunication stations etc.

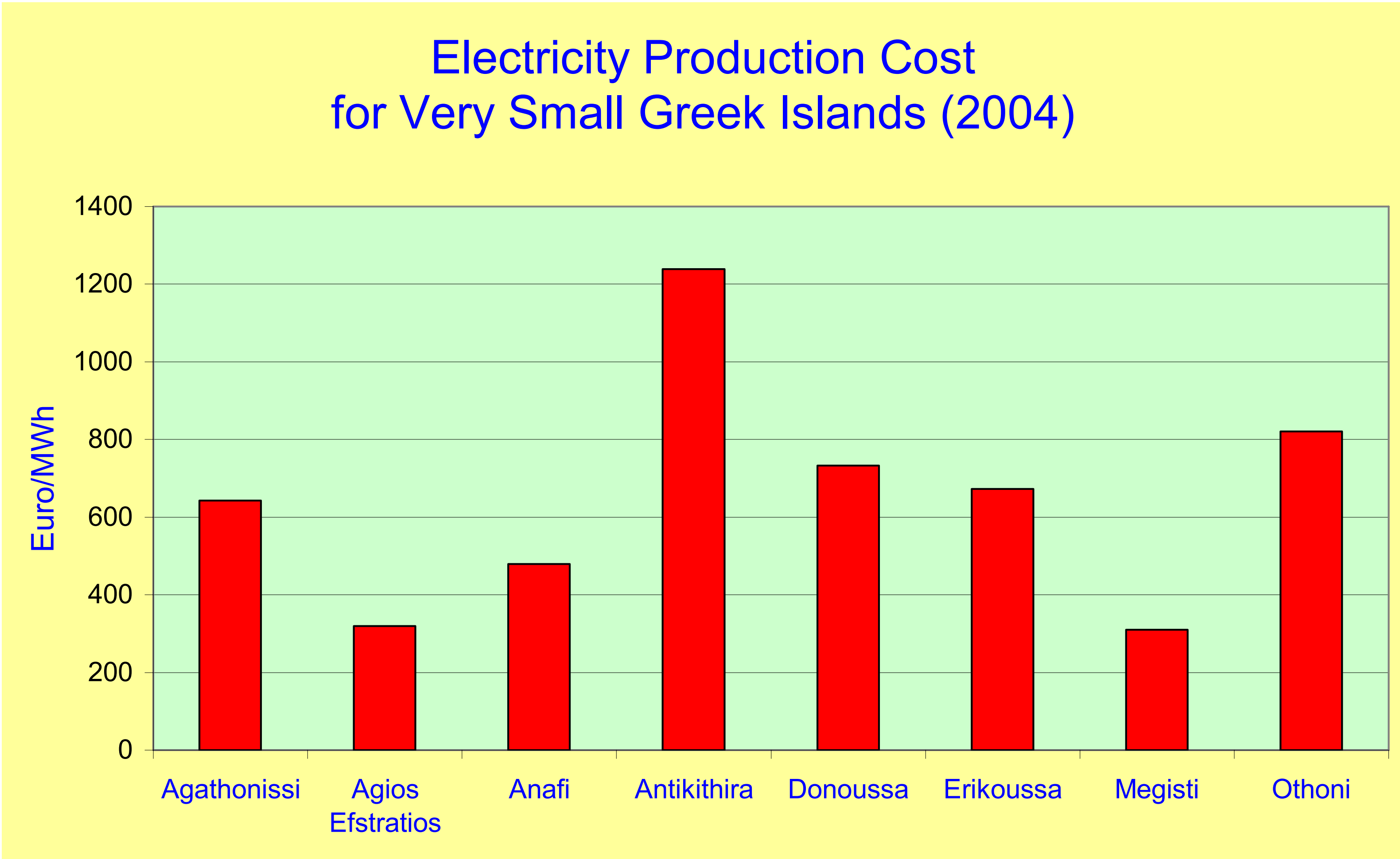
- On the other hand, Greece, being located in the SE European edge, possesses excellent wind and abundant solar potential

PROBLEM DESCRIPTION (cont.)

- Isolated consumers have no direct access to reliable electrical networks and cover their electrification needs using small diesel-generator sets.

- **RES based** (mainly wind power and photovoltaic driven) stand-alone systems have become one of the most promising ways to handle the electrification requirements of numerous isolated consumers worldwide.

High Electricity Production Cost



- In many cases, however, the necessary **energy storage equipment** contribution to the initial or the total operational **cost** is found to be dominant.

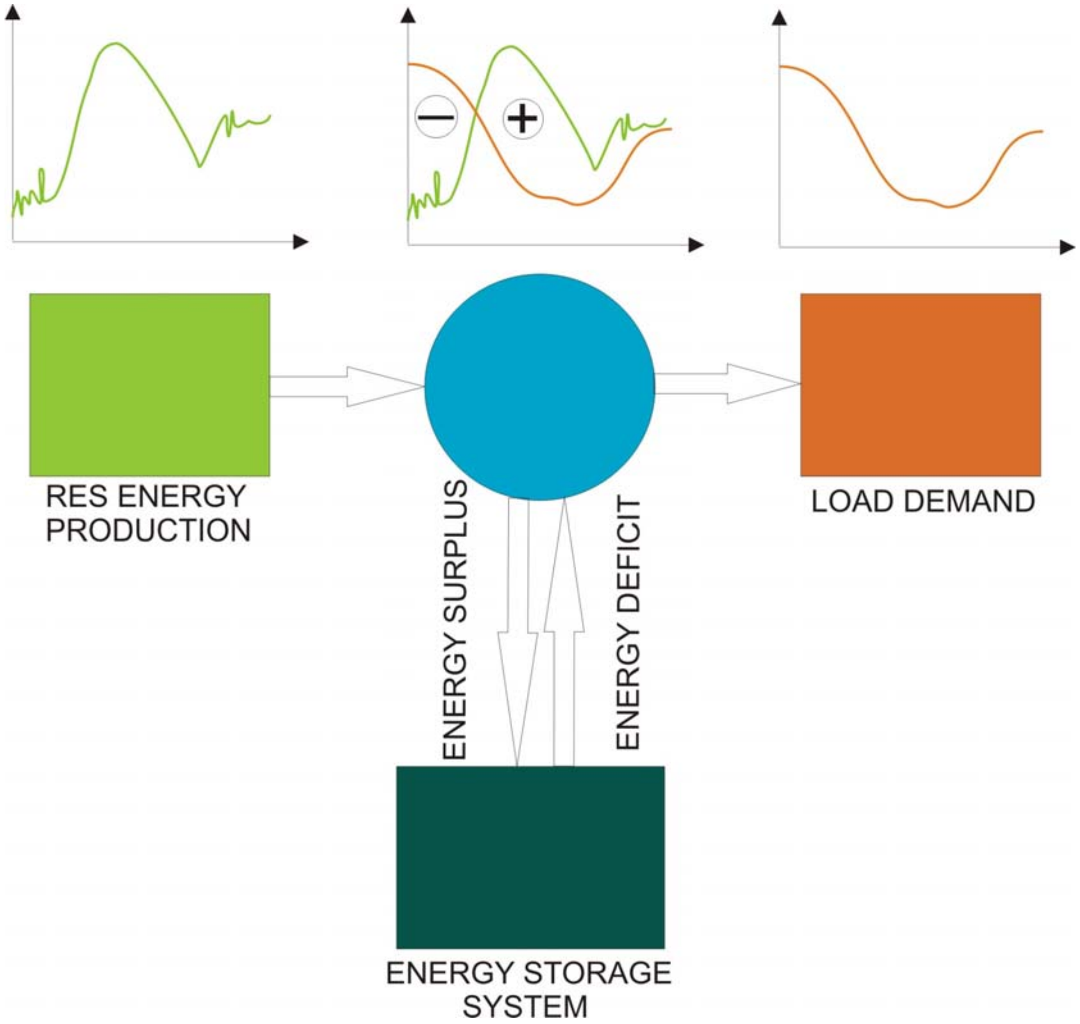
- For this purpose special emphasis is laid on the development of the appropriate energy storage configuration, in order to **minimize the lifecycle electricity production cost** of similar installations.

OBJECTIVE OF THE WORK

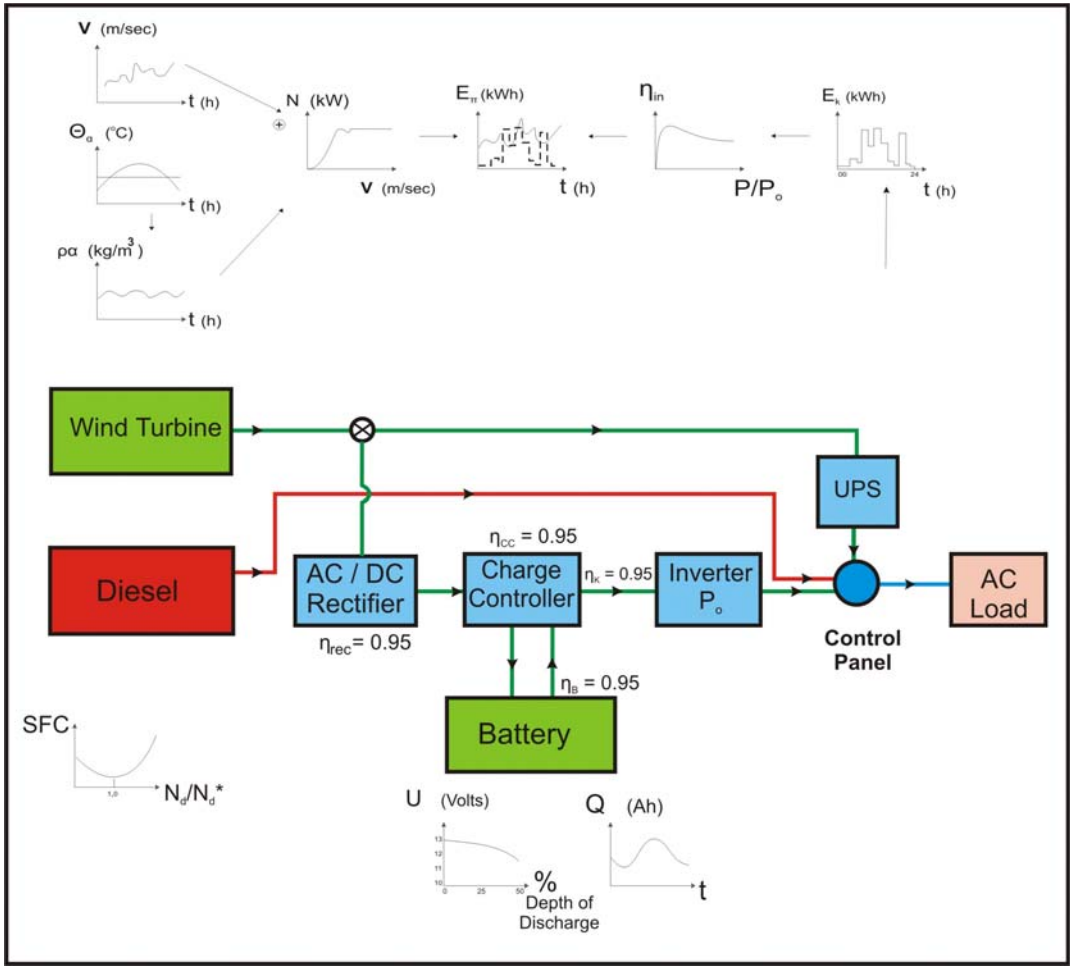
- to estimate the optimum dimensions of a representative RES based stand-alone system which,
- in collaboration with an appropriate **energy storage facility**,

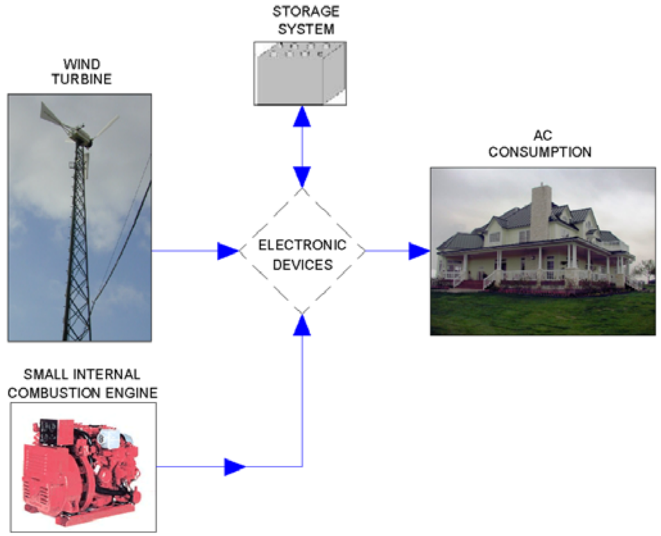
- guarantees the desired energy autonomy of several typical remote off-grid consumers located in representative territories at **minimum lifecycle electricity production cost.**

OBJECTIVE OF THE WORK (cont.)

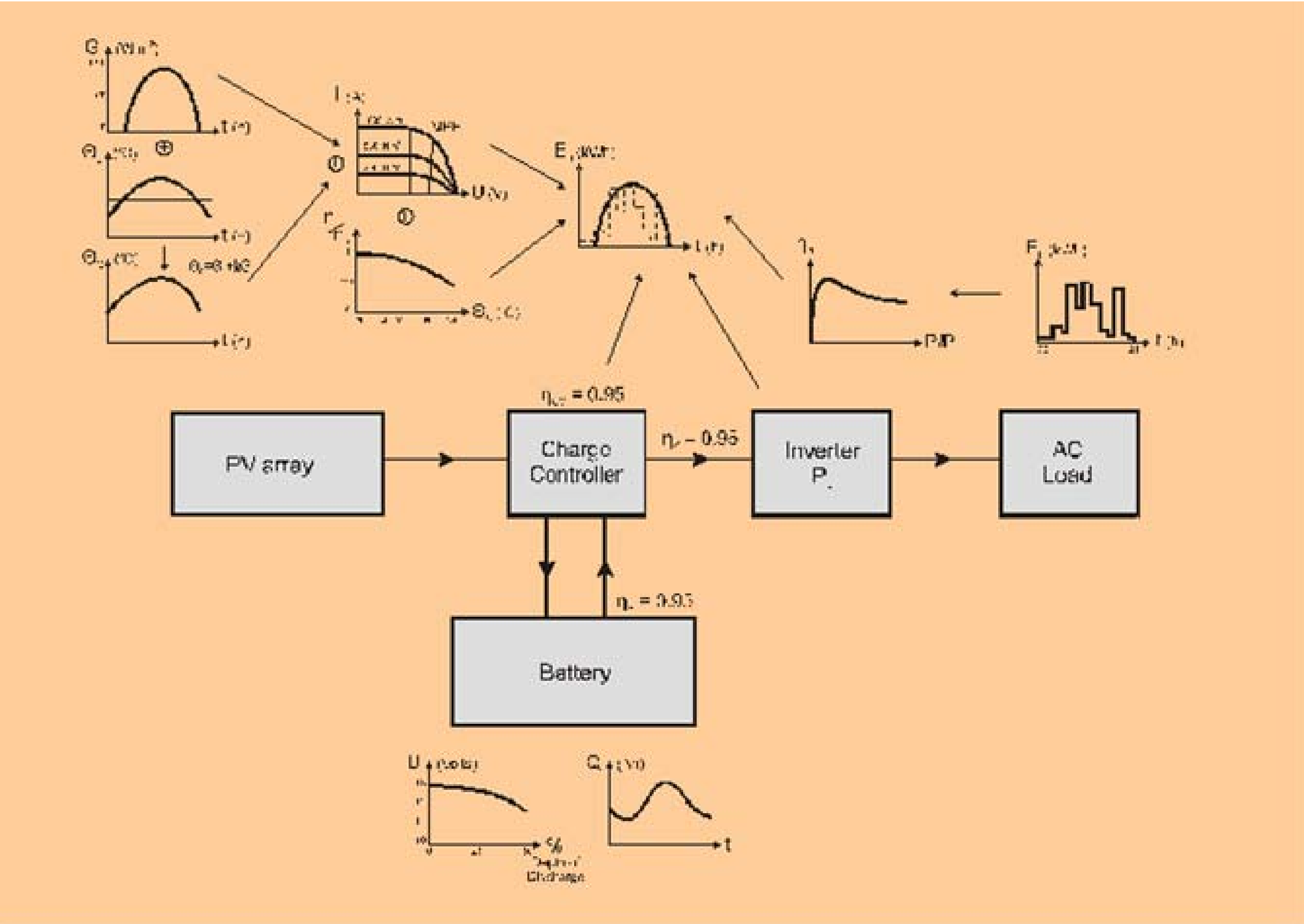


2a. PROPOSED CONFIGURATION (Wind Based Systems)





2b. PROPOSED CONFIGURATION (PV Based Systems)



3. STAND-ALONE SYSTEMS OPERATIONAL MODES

- The usual operational modes of the proposed stand-alone system during their long service period are:

- **The power demand is less than the power output of renewable energy station**. In this case the energy surplus is stored at the existing energy storage facility.

- **The power demand is greater than the renewable energy station power output,** which is not zero. In similar situations, the energy deficit is covered by the energy storage branch.

3. STAND-ALONE SYSTEMS OPERATIONAL MODES (cont.)

- **There is no renewable energy production.** In this case the entire energy demand is covered by the energy storage subsystem (ESS), under the condition that the energy storage device is not empty.

  For practical reasons, the utilization of **a small internal combustion engine** may be proposed in order to face unexpected energy production problems or situations related to "Force Majeure" events.

4. ELECTRICITY PRODUCTION COST ANALYSIS

- The present value of the entire investment cost of an off-grid RES based power system is a combination of **the initial installation cost** and the corresponding **maintenance and operation cost**, all quantities expressed in present values.
- The **initial investment cost** "IC_o" includes the market (ex-works) price "IC_{EP}" of the energy production equipment and the energy storage equipment purchase cost "IC_{ES}" as well as the corresponding balance of the plant cost "f".

$$IC_o = \left(IC_{EP} + IC_{ES}\right)\cdot(1+f)\cdot(1-\gamma)$$

"**γ**" is the subsidy percentage (e.g. 30%-50%)

ELECTRICITY PRODUCTION COST ANALYSIS (cont.)

- Special emphasis is set on the **energy storage system initial cost**, which depends both on *the energy storage capacity* and on the *output power* of the energy storage subsystem.

$$IC_{ES} = c_e \cdot E^{ss} + c_p \cdot N^{ss}$$

"**E^{ss}**" depends on:

- total annual energy consumption of the off grid installation
- participation of the ESS on the total energy consumption
- hours of energy autonomy
- total efficiency of the ESS
- maximum (permitted) depth of discharge of the ESS

4. ELECTRICITY PRODUCTION COST ANALYSIS (cont.)

- **The ESS rated power** "N^{ss}" is expressed via the consumption peak load demand, the efficiency of the energy production branch and the participation factor of the ESS on the coverage of the consumption peak load demand.

- **The Maintenance and Operation (M&O)** cost can be split into the fixed "FCn" and the variable "VCn" maintenance cost.

4. ELECTRICITY PRODUCTION COST ANALYSIS (cont.)

- **The fixed M&O cost** considers the **fuel cost consumed** by the diesel-electric generator. The annual fixed M&O cost can be expressed as a fraction of the initial capital invested, including an annual inflation rate describing the annual changes of labor cost and the corresponding spare parts.
- **The fuel consumption cost** is calculated from the annual diesel-oil quantity consumed, the current fuel price and the oil price annual escalation rate.
- **The present value of the variable maintenance and operation** cost "VCn" mainly depends on the replacement of major parts of the installation, which have a shorter lifetime than the complete installation, e.g. battery, diesel-electric generator, rotor blades, etc.

Energy Production Cost

The energy production cost results by dividing the present value of the installation total cost with the corresponding annual electricity production.

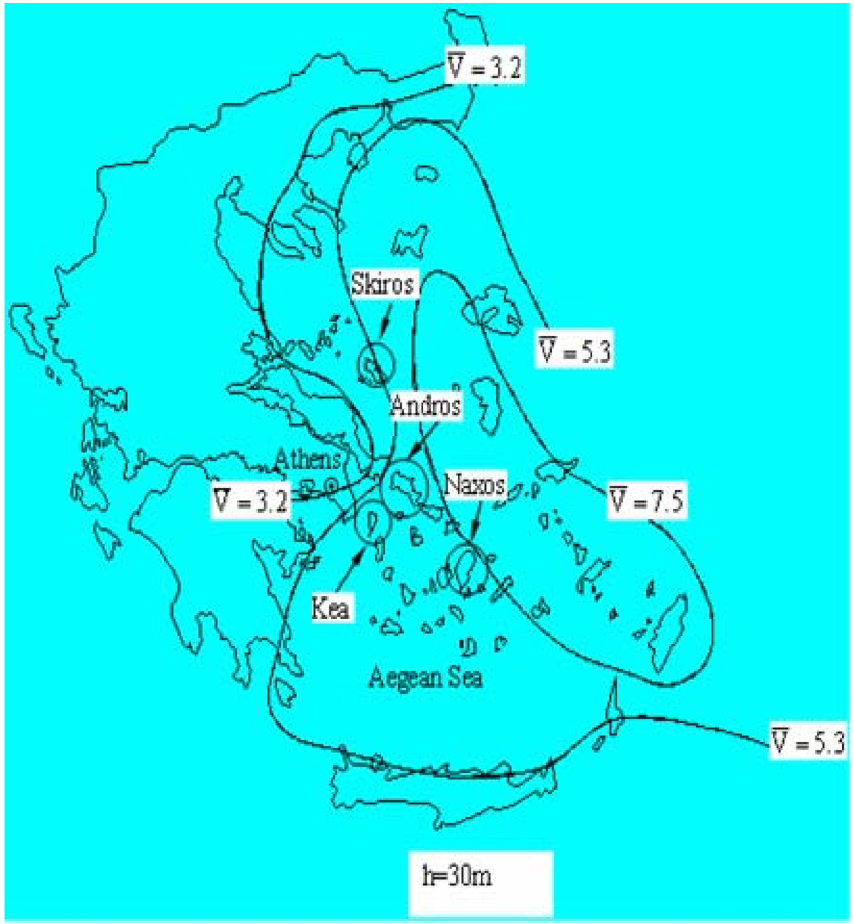
$$c_e = IC_{EP} \cdot \left(\frac{1-\gamma + m \cdot x \cdot \dfrac{x^n - 1}{x-1} + \Psi_{EP}}{\mathrm{E}_{tot} \cdot z \cdot \dfrac{z^n - 1}{z-1}} \right) + IC_{ES} \cdot \left(\frac{1-\gamma + m_s \cdot s \cdot \dfrac{s^n - 1}{s-1} + \Psi_{ES}}{\mathrm{E}_{tot} \cdot z \cdot \dfrac{z^n - 1}{z-1}} \right.$$

$$+ c_o \cdot M_f \cdot y \cdot \frac{\dfrac{y^n - 1}{y-1}}{\mathrm{E}_{tot} \cdot z \cdot \dfrac{z^n - 1}{z-1}} - \frac{\Upsilon_n}{\mathrm{E}_{tot} \cdot z \cdot \dfrac{z^n - 1}{z-1}}$$

First RHS term : cost due to the electricity production branch
Second RHS term : cost due to energy storage branch.
Third RHS term : cost related to the fuel production cost of any existing thermal power station.

5. Application Results

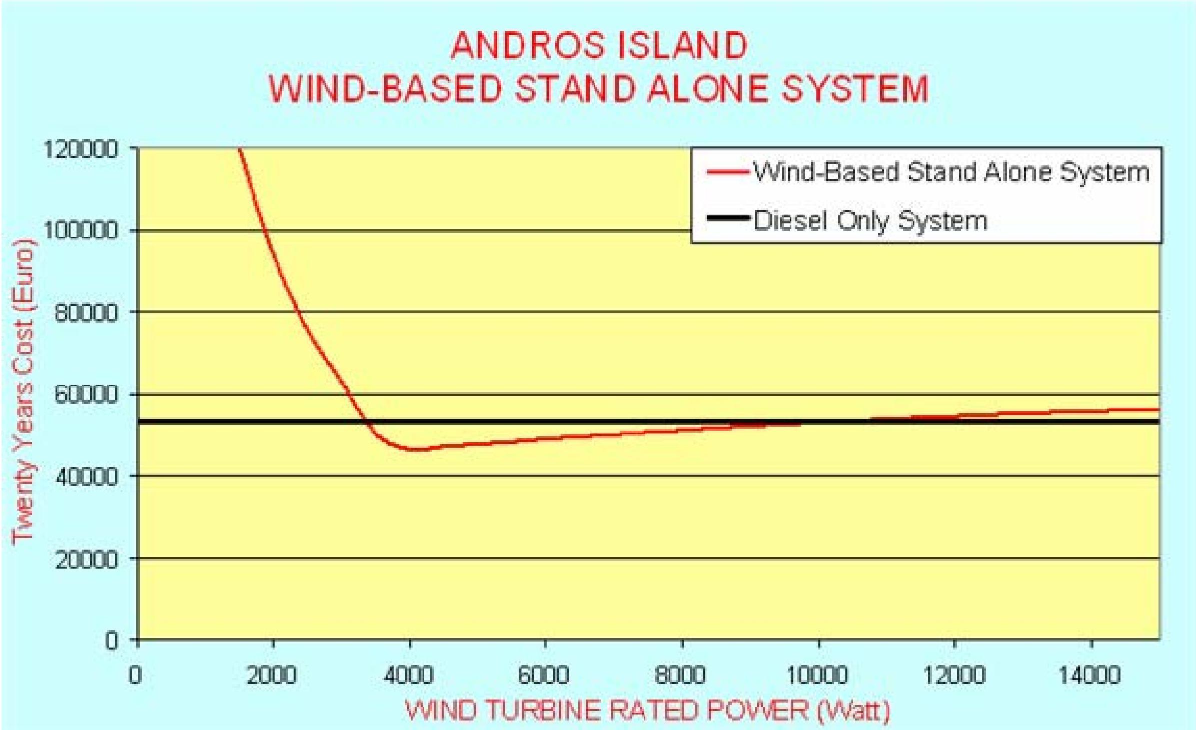
Wind-Based Off-Grid Solution for Remote Consumers



The first case concerns a remote consumer (3.5kW, 5000kWh per year) living in a medium-sized island of the Cyclades complex, i.e. Andros island.

The island has very good wind potential, while the minimum monthly average wind speed exceeds the 6.5m/s. The possibility of wind speed values below 4.0m/s in the area is slightly above 15% on long-term measurements basis.

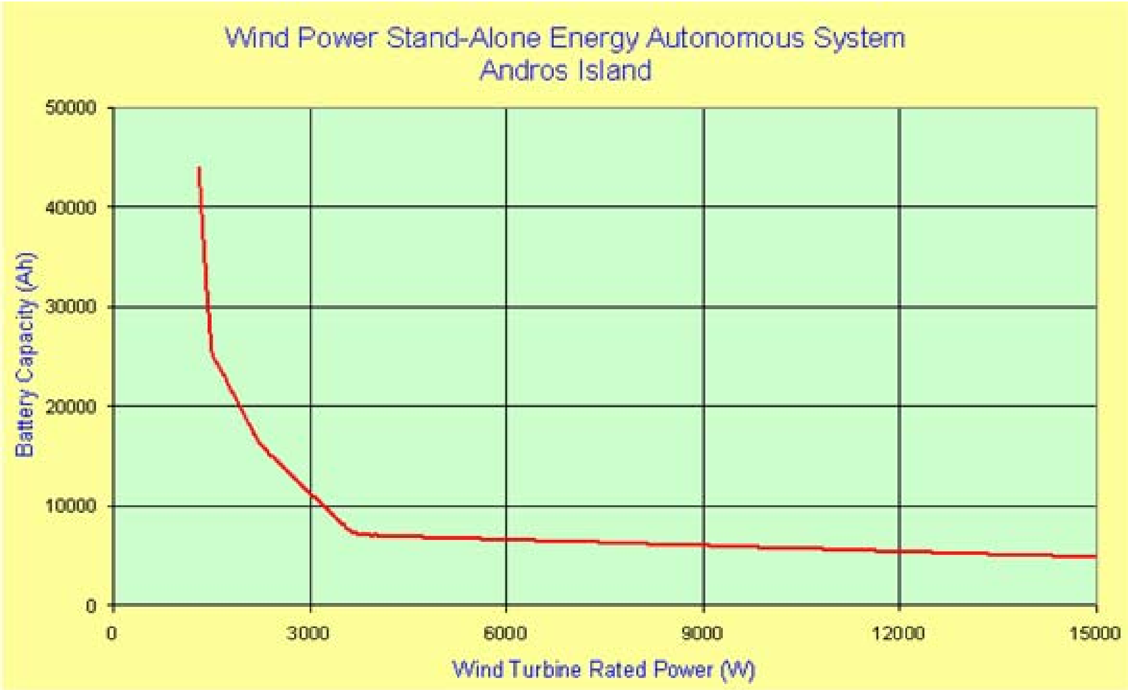
Wind-Based Off-Grid Solution for Remote Consumers (cont.)



A large variety of system configurations present **lower energy production cost** than the diesel only solution. There is an **optimum wind-only system** that operates at minimum electricity production cost.

The **minimum annual electrification cost** does not exceed the 2500€/year for a long service period of the installation.

Wind-Based Off-Grid Solution for Remote Consumers (cont.)



Wind turbine-lead acid battery configurations that **guarantee the energy autonomy** of the remote consumer.

There is a significant **battery capacity reduction** as the wind turbine rated power increases. This reduction is **more abrupt for small wind turbines**, while for larger engines the corresponding battery capacity presents milder decrease.

PV-Based Off-Grid Solution for Remote Small Islands

- Donoussa is a remote island of central Aegean Sea nearby Naxos.
- This case study refers to **a very small isolated electrical grid**, i.e. total annual electricity consumption of approximately **450MWh** and peak load demand of almost **225kW.**
- The photovoltaic based stand-alone system examined is capable to meet the electricity demand of the local habitants with the aid of an appropriate **energy storage system**. The autonomy range investigated suggests a **minimum of 2 hours** and a **maximum of 12 hours** to consider.
- The proposed system is expected (according to the hours of sunlight available and the corresponding load demand profile) to **cover directly** between the 20% and 50% of the local electricity consumption.

PV-Based Off-Grid Solution for Remote Small Islands

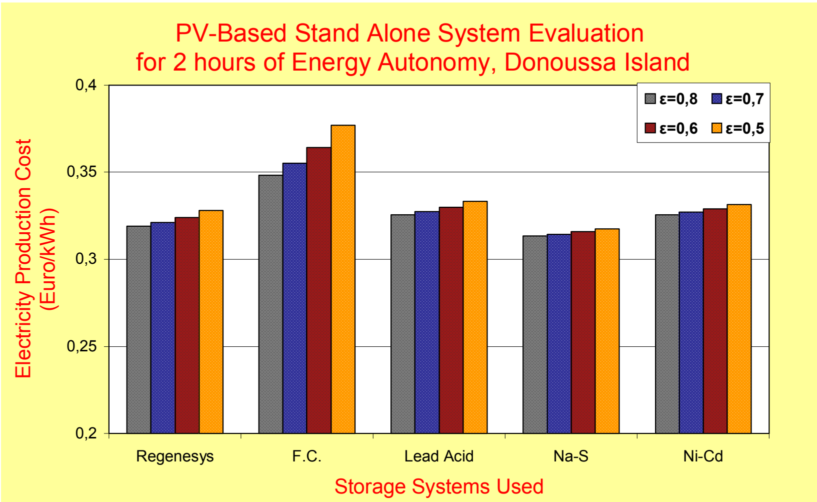
- The rest load demand is left to be covered by the PV panels and the existing internal combustion engines **via the energy storage installation**.

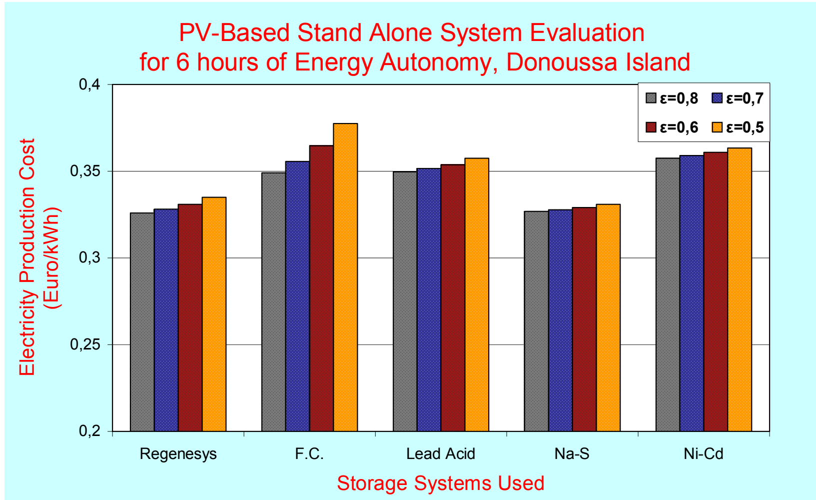
- The photovoltaic system if **properly sized** may be able to cover the charging of the existing storage system. In this case the energy storage subsystem can be employed in order to cover the rest of the consumption during the low (or zero) solar irradiance periods.

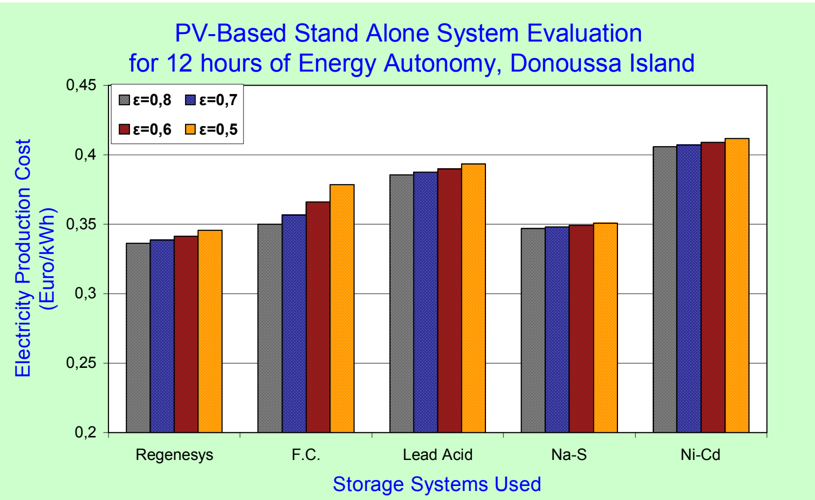
- The resulting **contribution of the corresponding ESS** as far as Donoussa is concerned varies between 50% and 80%, i.e. $0.5 \leq \varepsilon \leq 0.8$.

- Several ESS have been selected that can collaborate with the PV based installation. The systems proposed for evaluation are **conventional batteries**, **hydrogen storage incorporating fuel cells**, and the comparatively novel **flow batteries**. Larger systems such as PHS and CAES are not to be examined here.

PV-Based Off-Grid Solution for Remote Small Islands

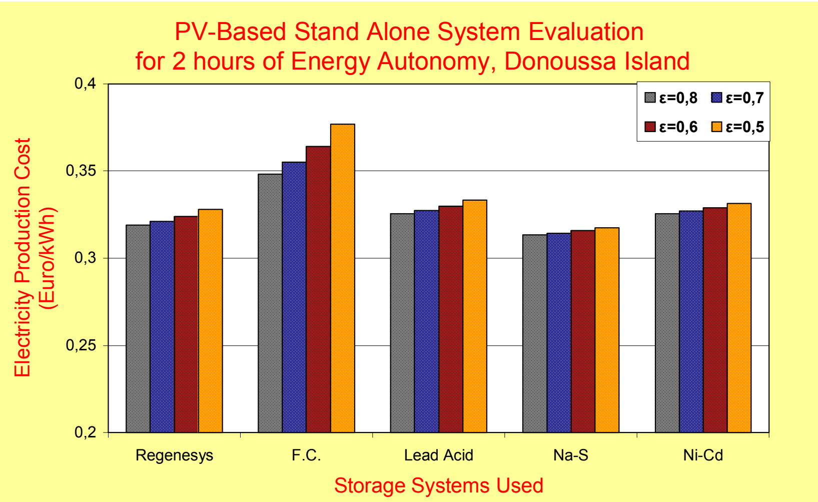


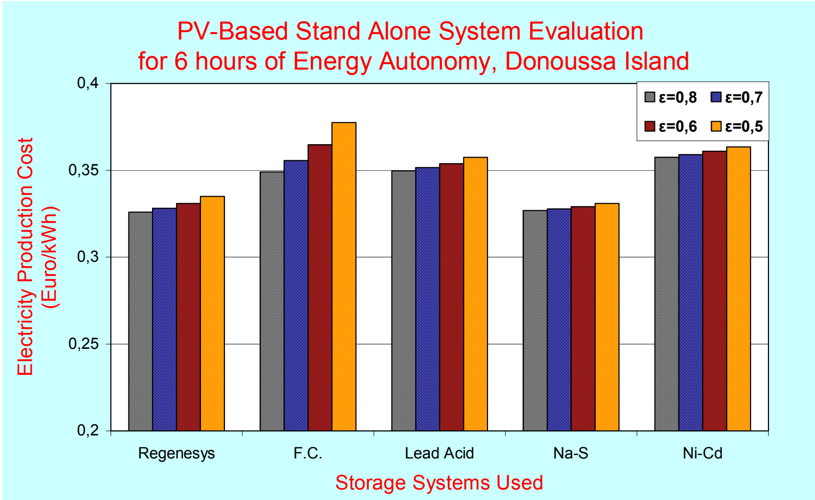


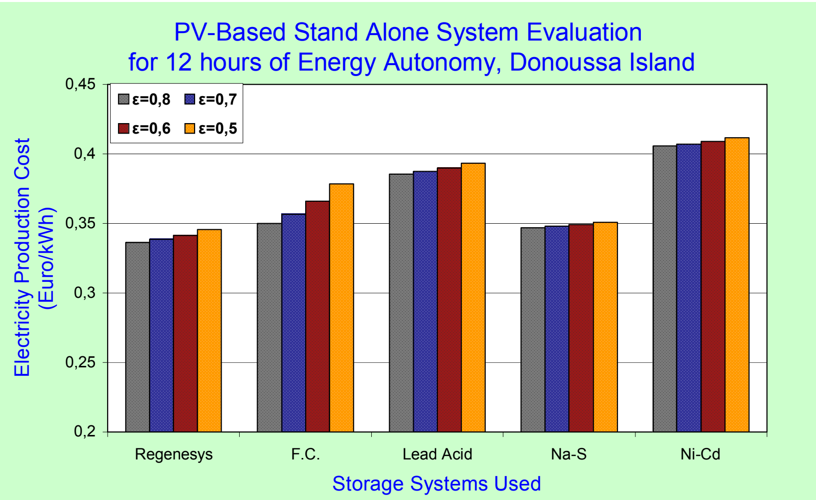


The most cost-effective solution appearing in nearly the entire autonomy range examined, apart from the 12 hours case, is the Na-S batteries. If we also keep in mind the high rates of energy density already discussed, the Na-S batteries may actually comprise a favorable solution.

PV-Based Off-Grid Solution for Remote Small Islands (cont.)







Taking into consideration the Na-S batteries limited operation owed to their moderate depth of discharge, if a higher autonomy is the dominant criterion, Regenesys and flow cells should be preferred.

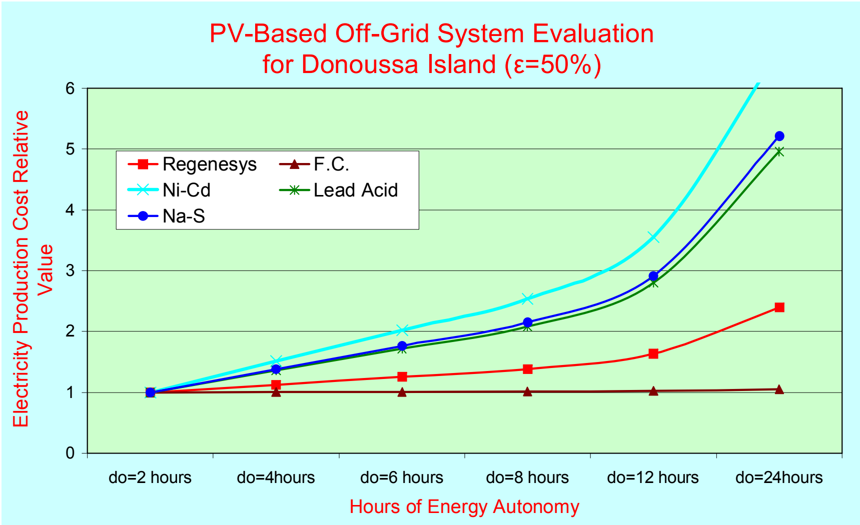
PV-Based Off-Grid Solution for Remote Small Islands (cont.)

- In respect to the fuel cells, the non promising results appearing for a few hours of autonomy tend to mitigate for a **higher duration of discharge**.

- Concerning the rest of the technologies investigated, it is clear that they have a similar behavior.

- There is a comparatively lower rate of cost increase presented by the **lead acid** batteries. However, in an overall evaluation, these systems should not be thought as promising solutions.

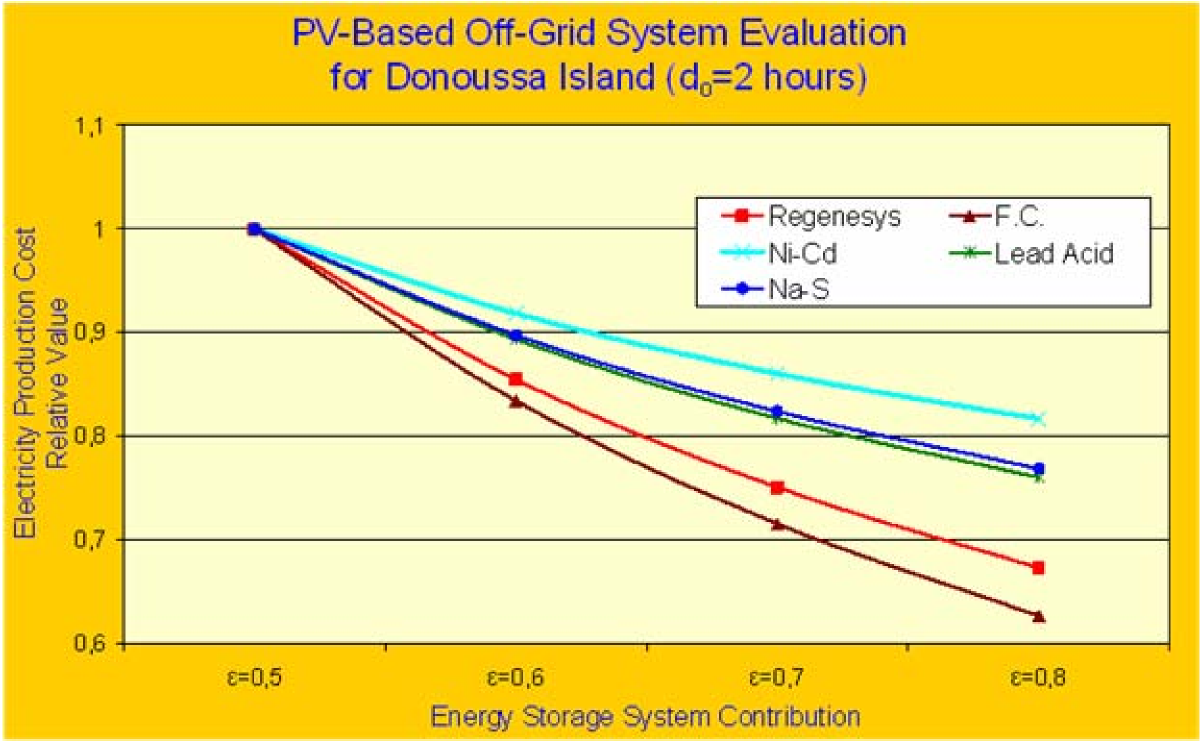
PV-Based Off-Grid Solution for Remote Small Islands (cont.)



Fuel cells are not affected by the autonomy increase, while the rest of the systems show a linear trend described by a proportional cost increase.

The Ni-Cd batteries present the greater slope, in contrast to the Regenesys batteries described by the mildest of them all.

PV-Based Off-Grid Solution for Remote Small Islands (cont.)



Regarding the energy contribution parameter **"ε" effect,** the opposite behavior may be encountered.

When the storage system is asked to cover a greater annual production share, fuel cells and Regenesys systems demonstrate the most significant cost reduction.

6. CONCLUSIONS

- An integrated energy production cost analysis for off grid installations, based on RES and energy storage configurations is presented.

- The proposed analysis takes into consideration the initial cost as well as the fixed and variable M&O cost of the entire installation (energy production & energy storage equipment).

- The developed methodology is applied to representative small off grid cases based on wind and solar potential exploitation.

6. CONCLUSIONS (cont.)

- Special attention is paid to demonstrate the impact of the energy storage systems utilized on the electricity production cost value.
- Using the proposed model one may select the most **appropriate configuration** for each case investigated.
- A properly sized stand-alone system in collaboration with the appropriate energy storage equipment is a **promising solution** for the energy demand problems of numerous existing isolated consumers all around the world.