# HYBRID SYSTEMS USING PUMP-STORAGE IMPLEMENTATION IN IKARIA ISLAND


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**ABSTRACT:** Although the majority of islands in the Aegean Sea are characterized by a great Aeolian potential, the converted wind energy cannot be fully absorbed. In addition, the electricity supply cost is very high and the operation of conventional engines is not only damaging for the environment but also uneconomical. Weak autonomous grids of islands are particularly sensitive to disturbances and thus stability problems arise with the operation of large *WT*. Consequently, it is essential to search for alternatives in the exploitation of cost-effective wind-power in insular areas and for systems with optimum cooperation between wind converters and other energy sources aiming at the maximization of economical wind-energy penetration. The object of the present research is to study a Hybrid System using medium-term pump-storage. The main tool of this study is the non-dynamic simulation of each subsystem's operation. This study aims to find the optimum size of each subsystem: i. the nominal power of WP to be installed, ii. the nominal power of the pump-station and iii. the capacity of the reservoirs. As long as the simulation results are presented and the optimization procedure is analyzed, the essay finishes with an economotechnical and sensitivity analysis. In Conclusion, the Hybrid System of Ikaria is an absolutely profitable investment.


## 1. STATING THE PROBLEM

The electrical supply of most islands in the Aegean Sea is carried out by autonomous diesel power stations. Due to the high load fluctuations internal combustion engines usually work with low efficiency. The situation becomes worst in smaller islands because of the higher load fluctuations. The result is excessive fuel consumption and, taking into account the high price of oil, an extremely high cost of electricity supply in islands.

To be precise, the electricity supply cost in Ikaria for 1999 was approximately 18.1 eurocents/kWh. The expense for fuel and lubricants contributed to this cost with 8.3 eurocents/kWh. The rest of the expenses concern payment of wages, financial expenditures, fixed assets depreciation and general expenditures of administration. Ikaria is a average size island of the Aegean from population and energy demand aspect. Local people are almost 7,500, but in the summer the population can become as high as 30,000 due to tourist activity.

In insular areas the installation of WTs was suggested many years ago. It is a technologically mature solution for the confrontation of high electricity supply costs. In the existing electrical system of Ikaria 7 WTs have been operating since '91 in addition to the conventional station in Agios Kirikos. The WTs are installed in the location Perdiki about 10 km from Agios Kirikos, the capital of Ikaria. The conventional electrical system of Ikaria consists of:

- Central Station: 8 diesel gensets of total power **6,900 kW**.
- Wind Park: **7 x 55 kW = 385 kW**.

All the WT's are Windmatic 15S, a fixed speed and stall model. The distribution grid has radial form and is composed of 3 mid-voltage lines of 15 kV.

Unfortunately, wind energy penetration in a traditional autonomous system cannot reach a satisfactory level due to the technical minimum of conventional units. In addition, problems appear with the cooperation between fixed speed WT's and gensets and with the stability of the already week grid. Finally, the situation is further deteriorated by the stochastic nature of wind, which doesn't blow according to the consumption needs.

Especially in Ikaria, there is a problem due to the absorption of reactive power from the WTs at hours of low demand. In addition, the wind turbulence creates high fluctuations in the load that diesel engines sustain. This results to their inefficient operation. That's why -mostly during winter months- it is required to disconnect some or even all WTs *(s. fig. 1)*. These disconnections mean low energy exploitation per installed kW, which will be further reduced if additional WTs are to be installed without changing the whole philosophy of the system which considers WTs as secondary energy source.

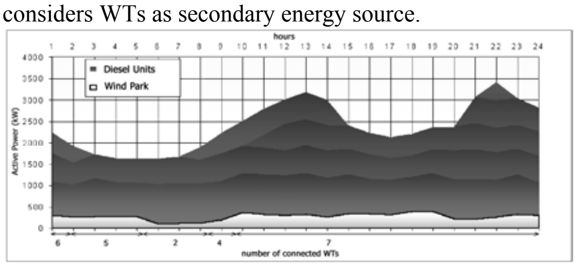


Fig. 1: Production synthesis of 12.07.98. The forced disconnections of WTs due to low load are distinguished on morning hours.

In particular, total electrical consumption of 1999 in Ikaria reached 19,650 MWh and the production of WT's was about 1,079 MWh, which corresponds to 5.5% contribution to the whole production. From generation data of 1994 up to 1999 it is ascertained that the capacity factor $C_f$ fluctuates around 31% with a maximum value 38,5% in 1998. Knowing the Weibull distribution of site Perdiki *(c=9.31 m/s k=1.68)* rejected wind energy can be estimated regarding the availability factor as 0.95. We calculate the rejected energy due to obligatory cutoffs for 1998, when all WT's were operating without any problem, to be 13% of possible production or about 192 MWh.

## 2. THE SOLUTION - RES HYBRID SYSTEMS

In order to succeed maximum penetration of RES and especially of wind energy the whole system should be designed from scratch so that WT will be the main energy source, contrary to conventional units which will have only supplementary and backup role. Surely, the development of power electronics accelerated the release of WTs from conventional units and the formation of Hybrid Systems.

**Hybrid systems of autonomous grids are defined as energy systems that combine different energy sources**

**aiming to the maximization of economical penetration of RES and particularly of Wind Energy. The finest cooperation of the combined Energy Sources and the reduction of electricity supply cost per kWh should be pursued accompanied by improvement of the electrical power quality.** [2]

The construction of a dam by the Ministry of Agriculture in 1993 has created a lake with total capacity 910,000 $m^3$. The lake is located in Pezi, **720 m** above sea level and covers the water supply and irrigation needs of municipalities Raches and Agios Polykarpos. This fact in combination with the great aeolian potential of the island *(with Mykonos they lie on the region of Aegean with the highest annual wind velocities)* is a good opportunity for the implementation of the first **pump-storage** hybrid system of Greece in Ikaria Island.

The Hybrid System of Ikaria will be the first Integrated Pump-Storage, but not the first Hybrid-System in Greece. Since June 2000 the Hybrid System of Kythnos has been supplying Kythnos with almost 30% RES penetration. For further information refer to source [2].

A Hybrid System must be comprised of the subsystem of RES units *(Wind turbines)*, the storage subsystem *(pump-storage)*, the subsystem of conventional units *(as stand-by only)* and the central unit of power conditioning & control.

Just as the central control unit is the "brain" of a Hybrid System, the storage subsystem is its "heart". Storage units may complete different aims. For instance, short-term power fluctuations can be flattened in order to improve power quality. Furthermore, storage units can reduce costly cycling of diesel engines, conduce in efficient operation of diesel engines, balance between long wind power surplus and long lack of wind power or/and avoid the operation of conventional units for a long period. From technological point of view there are many different types and each one fulfills some or rarely all the aforementioned aims.

In particular, pump-storage has the following advantages:

- It is able to store huge amounts of energy contrary to other kinds of storage and in fact the bigger the capacity and head between reservoirs the more is the potential energy stored.
- Energy can be absorbed and extracted in high rates.
- Hydroturbines can start operating immediately. During operation the adjustment of power and the response to fluctuations is fast enough. *(Especially Pelton turbines).*
- Because the water is recycled, practically it is not required continuous flow from upper basin.
- Reservoirs may have other usages, like as watering irrigation, fire protection of forests, sports and fisheries.

Reversible Hydroelectric Plants have been already constructed in many spots in Greece for pump-storage on low demand hours and coverage of peak loads on high demand hours, so that the necessary experience and know-how are available.

The choice of variable speed Wind turbines for the Hybrid System of Ikaria is compulsory, because in the Aegean Sea in contrast to wind conditions of N. Europe, winds are described by high turbulence and intense gusts. In addition, autonomous grids of most islands have special requests.

## 3. STRUCTURE OF HYBRID SYSTEM

After the optimum sizing *(s. section 5),* it is recommended that the hybrid system should be composed of:

- **Wind Energy Subsystem:**
  - -New WP with var. speed WTs: **9 x600 kW = 5,400 kW**
  - -Existing WP with fixed speed WTs:**7x55kW = 385 kW**
- **Subsystem of mid-term energy storage:**
  - **-Station A:** at an altitude of **560 m** with **one** Pelton turbine of **900 kW** and an operating head of **160 m**, which will exploit only the seasonal overflows of the dam. The first concrete tank will be constructed downstream after station A
  - **-Station B:** at **65 m** with **two** Pelton turbines, each one of 1.400 kW and an operating head of **480 m**. Likewise the second concrete tank will be constructed just after station B.
  - **-The pump plant** will be positioned next to station B with pumps in parallel connection, each one with power of **160 kW**. Water pumping and recycling will be done only between the two concrete tanks of equal volume.

  The most suitable number of pumps and tank's capacity are subjects of research.

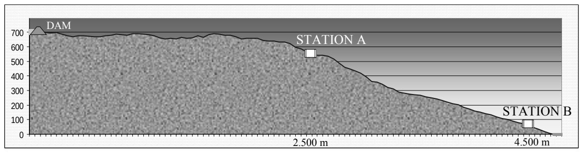

Figure. 2: Section plan of SHP and position of 2 tanks and stations.

After optimization, suggesting power of pump plant is **10x160=1,600kW** and tank's capacity is **60,000 $m^3$**.

- **Conventional PowerStation: 6.900 kW** *(as it was).*

Target of Hybrid System is the maximum exploitation of wind power directly to consumption. Autonomous operation of WTs has become easily applicable and viable with certainly high power quality, as a result of the rapid development of power electronics. Pumps will be supplied only with the surplus wind power ensuring that way the most efficient operation of integrated hybrid system.

Hybrid System of Ikaria will be capable of feeding the grid for long periods exclusively from RES. Two basic modes of operation are distinguished. When WTs cannot cover the load completely due to reduced wind speed or high demand load, the shortage will be completed by hydroturbines. The upper tank *(buffer)* will be emptied and the lower will be filled. Reversely, with excess wind-power WTs will supply exclusively the grid and the rest of the power will be used for pumping water from lower to upper tank *(fig. 3)*.

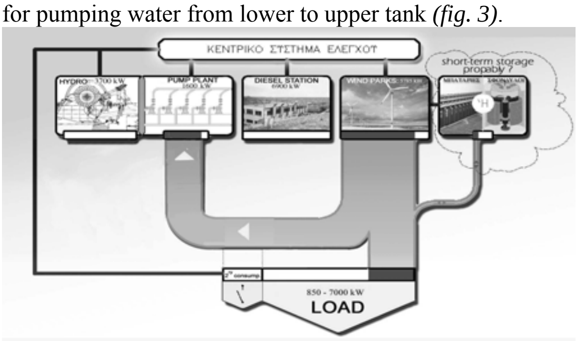

Figure 3: Wind power surplus is fed to the pumps *(100% RES)*

### 3.1 Optimal Cooperation of Subsystems.

Except for right sizing and selection of each unit, of great importance for the efficient operation of Hybrid System is the harmonic cooperation between them. The section of Hybrid System, which undertakes the task to accomplish this objective, is the Control and Energy Management System. It will be composed of Central Unit of Power Conditioning and Supervisory Control, Local Dispatchers and Controllers of each subsystem and the Communication and Signals Transmission Net.

Possible operation modes of Hybrid System result from the permissible combinations of possible operation modes of each subsystem separately. It is convenient to represent the operation mode of Hybrid System with a matrix. This is an array of 5 elements just like the following:
[WP, HA, HB, DG, SC]. The two-lettered symbols represent the 5 subsystems and are allowed to get definite values that mean: 0-stop operation, 1-start operation,
2-pumping *(only for HB),* 3-stand by.

The desirable mode is determined by current wind power and load demand, while water level in tanks is considered too. The determination algorithm is a sum of logical operations and conditions, but is too large to be presented in this paper. The mode determination algorithm was used in Hybrid System's simulation.

## 4. MODELISATION AND SIMULATION

Programming and simulation code writing was done *in Matlab* environment**.** It was well studied, so that the most important parameters *(controlled and non)*, which influence the operation of Hybrid System, were considered. Simulation's type is long-performance *(non dynamic)* using hourly timeseries. Each unit of the system was modeled in a separated routine that was called from the main program:
**a) Windturbines**. Characteristic velocity-power curves were taken from different variable speed models. Among them is OA600 that was designed and made in Greece. Anemological data were reduced from the typical height of 10 m to hub height with the suitable roughness length.
**b) Variable speed pumps.** During the simulation **operation point** and naturally efficiency is calculated in function to current **required power to absorb**. Each operation point refers to a unique combination of valve opening, operation speed and number of operating pumps.
**c) Hydroturbines.** Typical variation of efficiency (for Pelton turbines) as function to flow variation is considered.
**d) Diesel units**. According to data from Central Station of Ikaria the relation between power *P (kW)* and *specific consumption* $b_e$ *(gr/kWh)* is approximated by a fitted polynomial. This gives the hourly fuel consumption.
**e) The Central Unit of Supervisory Control** is simulated by a set of logical operations, which have as input the wind power surplus and the availability of water in the tanks and as output the desirable operation mode.

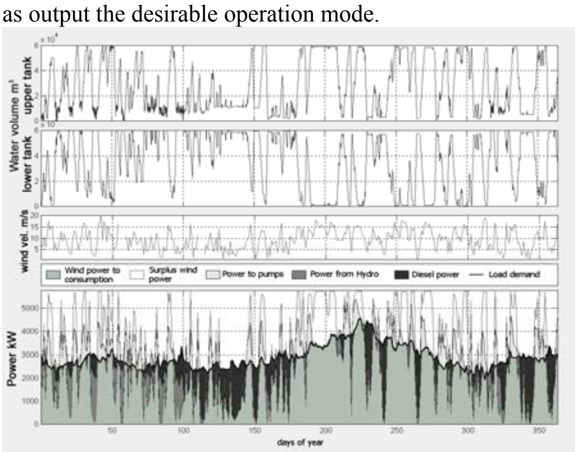


Figure 4: Annual power distribution of Hybrid System during 2003

Finally, the simulation of reservoirs was carefully developed in order to present realistically their repletion and evacuation. Afterwards, some diagrams of power distribution and of water exchanging between lower and upper tank are presented. These result from the simulation program for years 2003 and 2005.

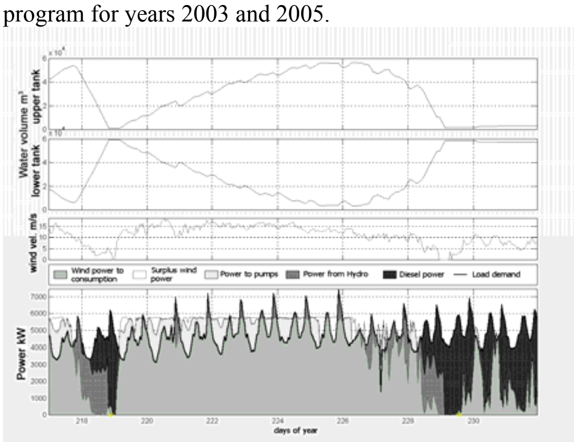


Figure 5: Power distribution from 6th to 20th August 2005.

## 5. THE OPTIMUM DIMENSIONING

The optimum dimensioning consists in finding the best size of various elements that compose the Hybrid System ie:
i) The nominal power of WP to be installed.
ii) The number of pumps each one of 160 kW.
iii) The capacity of the two concrete reservoirs.

As soon as the simulation code is written and after estimating future load, the optimization algorithm begins. The objective function to be minimized is the electricity supply cost per kWh or equally the annual el. supply costs.

From simulation of Hybrid System's operation for year 2002 the percentage of RES (WT and Hydro) in overall annual energy supply is calculated. Besides, annual fuel consumption from conventional units is calculated. Numerous simulations with different configuration each time have been executed.

Moreover, the annual expenditures, which constitute the annual electricity supply cost, were calculated for each different configuration. The partial expenditures, which shape the annual electricity supply cost, are the annual investment charge, the operation and maintenance costs of WT and Hydro and the fuel cost. The parameters for each configuration were the three abovementioned sizes. In that way, three curves, which represent the annual supply cost towards each of the three parameters, are drawn.

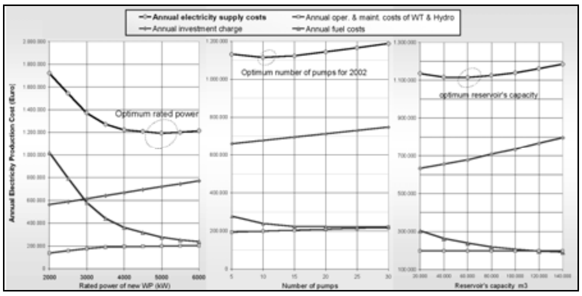


Figure 6: Optimum values for the 3 sizing parameters.

The optimum value for each parameter is located on the minimum of the corresponding curve. The optimum configuration was analytically presented in section 3.

### 5.1 Capital Costs Analysis

As a project of RES technology, EU supports the implementation of the Hybrid System of Ikaria up to 40%. The total investment is evaluated for each different configuration according to table I. In this table the expenditures are divided into constant and variable according to the 3 known parameters.

The price of WT is estimated to be 1000 EURO per installed kW. This is the current price of middle size WT (500-700 kW). We calculate the annual investment charge from the total capital costs after subsidy, considering a 6% interest rate and an repayment period of 20 years.

| Category | Variable Investments | Parameters | Cost |
|---|---|---|---|
| A. | Rated power of WP to be installed | 5.400 kW | 5.400.000 Euro |
| B.1 | Number of pumps (+inverters) | 10 units | 665.000 >> |
| B.2 | Capacity of reservoirs | 60.000 $m^3$ | 1.385.000 >> |
| | **Constant Investments** | | |
| B. | Rest expenditures for Hydropower facility | | 2.862.580 >> |
| C. | Control and Energy Management System & SCADA | | 580.000 >> |
| D. | Design-engineering, supervision & co-ordination e.t.c. | | 958.000 >> |
| | | **Sum of subsidized investments** | **11.850.580** >> |
| | | - 40% subsidy | 4.740.232 >> |
| | | **After subsidy** | **7.110.348** >> |
| E. | **Non-subsidized projects:** Network upgrade &expansion | | 1.390.000 + >> |
| | | **Overall project investment** | **8.500.348 Euro** |

Table I: Parametrical presentation of the overall project budget.

### 5.2. Significant Ecological Benefits

If the optimum configuration of Hybrid System is adopted, the wind energy penetration with recovery of stored energy for year 2003 will be 76,2%. The participation of all RES *(WTs & Hydro)* to the annual production can reach 82,5%. The production of each subsystem for the same year is shown in table II.

| Prospective consumption | 25.400 MWh | 100 % | Produced Wind Energy Allocation | |
|---|---|---|---|---|
| **Production of WT** | 16.902 MWh | 66.5 % | Direct consumption | 61.1 % |
| **Production of Hydro** | 4.043 MWh | 16.0 % | Pumping | 15.5 % |
| **Production of Diesel** | 4.455 MWh | 17.5 % | Dump | 22.9 % |

Table II: Data from Hybrid System's simulation for 2003.

The expected diesel-fuel consumption of the conventional system is for 2003 **6,654 tons**, while with the Hybrid it is reduced to **988 tons**! This way, we avoid the emission of 18,130 tons or 9 million $m^3$ of $CO_2$ per year.

## 6. FINANCIAL EVALUATION

The profit from the operation of the Hybrid System is estimated more easily taking into account the reduction of electricity supply cost in relation to the previous situation.

**In order to compare correctly the supply cost per kWh of the Hybrid System with the supply cost per kWh of the Conventional System, we must ignore all other costs other than fuel** *(payment of wages, depreciation of conventional equipment, administration, financial and other expenses)***, which remain unchanged or at least they are independent from the construction and operation of the Hybrid System.** That's why, we consider as comparative cost for the Conventional System the fuel and lubricants costs and as comparative cost for the Hybrid System the sum of annual investment charge, the maintenance and operation costs *(for WTs and Hydro)* and the new fuel and lubricants costs.

So, the el. cost of the Conventional System for 1999 was **8.3 cEURO/kWh**. Correspondingly, the electricity cost for the Hybrid System for 2003 is estimated to be **5.0 cEURO/kWh** taking the fuel prices in Ikaria of 1999. This means a relative profit equal to **3.3 cEURO/kWh**.

### 6.1 Annual Profit Course

The annual profit will be around **768,900 EURO** for year **2002** and according to the load prediction it will go as high as **1,150,400 EURO** for **2010**.

The purchase of 2 diesel engines, each of them with 4,5-5 MW power, is scheduled due to continuous increase of load. Fortunately, if the Hybrid System is constructed, only the installation of one engine will be necessary. So, taking into account the advantage profit of non-purchasing one diesel engine worth approximately 3.7 millions EURO *(less than half the total investment for the Hybrid System)*, the annual profit from the Hybrid System's operation will be **1,156,000 EURO** for 2003 and will grow to be as high as **1,470,300 EURO**. That way, the **amortization period** of this project is considered to be only **4** to **5 years** at most.

### 6.2 Sensitivity Analysis

Finally, we will examine the sensitivity of the relative profit per kWh to the following unexpected factors: Mean annual price of fuel, annual wind energy production, interest rates and annual operation and maintenance costs. From the figure 6 we realize that the most influencing factor to the earnings is the future price of fuel.

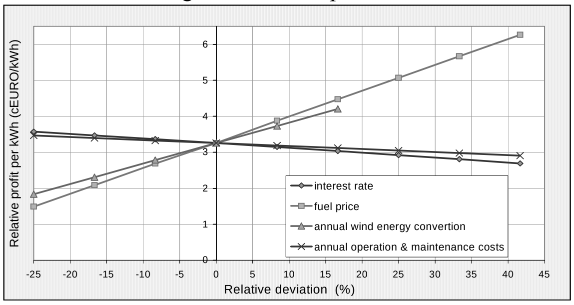


Figure 7: Sensitivity of relative profit per kWh.

**The more expensive fuel gets, the more profitable the operation of the Hybrid System is.** This fact is very promising, because the fuel price has a long-term upward tendency due to the world's low oil reserves.

## 7. CONCLUSION

We come to the conclusion that the construction of the Hybrid System in Ikaria is a very attractive investment. Besides, if we take into account the strictly non-financial benefits, like the environmental protection, the release from the imported oil in Greece and the creation of a tourist attraction pole for scientists and generally people with ecological sensitization, then the implementation of Ikarian Hybrid System is a present necessity.

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