A holistic approach towards optimal planning of hybrid renewable energy systems: Combining hydroelectric and wind energy (1)

European Geosciences Union General Assembly 2014, Vienna, Austria, 27 April-2 May 2014, Session HS5.4/CL4.8/ERE1.16

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1. Abstract

Hydropower with **pumped storage** is a proven technology with very high **efficiency** that offers a unique **large-scale energy buffer**. Energy storage is employed by pumping water upstream to take advantage of the excess of produced energy (e.g. during night) and next retrieving this water to generate hydropower during demand peaks. Excess energy occurs due to other **renewables** (wind, solar) whose power fluctuates in an uncontrollable manner. By integrating these with hydroelectric plants with pumped storage facilities we can form **autonomous hybrid renewable energy systems (HRES)**. The optimal planning and management thereof requires a holistic approach, where uncertainty is properly represented. In this context, a novel framework is proposed, based on **stochastic simulation** and **optimization**. This is tested in an existing hydrosystem of Greece, considering its combined operation with a hypothetical wind power system, for which we seek the optimal design to ensure the most beneficial performance of the overall scheme.

2. Motivation: The global challenge of renewable energy

With the emergence of the **global economic crisis**, questions about the model of energy production and the possible waste of finite natural resources are raised. The problem is highlighted after the **oil crisis of 1973**, with an emerging need to move to a **new model** with the increased role of renewable energy in the energy balance. Under the "20-20-20" draft of the European Union, a penetration of renewable energy sources to **20% on energy consumption by 2020** has been set. Despite the rise in oil prices (Fig. 1) we observe a parallel increase in global energy consumption (with a few exceptions, explained by the demand decrease connected to the crisis), suggesting the need for the production of **new forms of energy in the direction of sustainability** with a parallel decrease in consumption. Figure 2 depicts the primary energy use (before being converted to another fuel use) in kilograms of equivalent oil per capita from 1960 to 2011. The drop in consumption after 2008 is due to the beginning of the economic crisis.

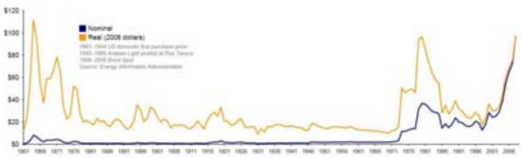

Fig. 1: Long-term oil prices between 1861 and 2007; the orange line adjusted for inflation, blue without inflation (Source: http://upload.wikimedia.org/wikipedia/commons/8/87/Oil_Prices_1861_2007.svg).

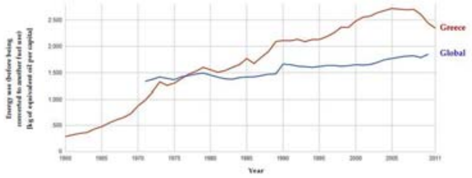

Fig. 2: Energy use between 1960 and 2011. Comparison between the consumption in Greece and the global average (Source: World Bank, http://data.worldbank.org/).

3. Reliability concepts in renewable energy generation

Reliability is defined as the probability of achieving a particular performance for a specified period of time and under specific conditions. Complementary to the concept of reliability is the probability of failure, defined as $\alpha = P(X < x^*)$, where X is a random variable expressing a quantitative performance index of the system (such as release, energy production, etc.) and x^* the target value of that quantity. Here the reliability refers to the possibility of fulfilling a target of energy production. The concept of reliability is extended to include the reliable performance of the system: x^* is the target value that the system can achieve for a certain level (e.g., 99%, 97%, 95%), thus $\alpha^* = P(X \geq x^*)$. Firm energy is defined as the guaranteed hydroelectric energy that can be produced under a given hydrological regime, in order to meet the energy demand with a very high reliability. The surplus energy is called secondary. The economic value of firm energy is much higher than the value of secondary energy; typically, a 2:1 ratio is considered.

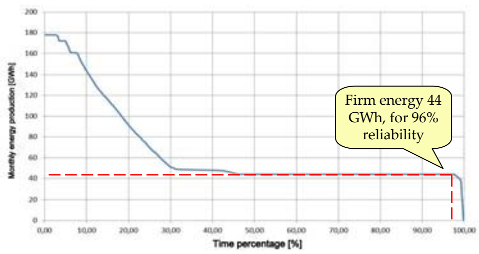

Fig. 3: Energy-duration curve of a hydroelectric plant, obtained through simulation. The primary energy is 44 GWh for 96% confidence level (the baseline period is monthly).

4. Renewable energy storage through pumping

The electric energy production from power plants (thermal, hydroelectric, etc.) is adjusted in accordance with the predictable time-varying load. In periods of low demand, large thermal power stations do not have the technical means to reduce their production below a technical minimum. This shortcoming creates excess of energy generation. This instability is exacerbated by the increased participation of renewable energy into the grid. The wind velocity and solar radiation are stochastic variables, therefore their energy production is time-varying and inconsistent to the demand patterns. This imbalance is weighted by storing energy during periods of low demand returning it to the network in peak periods, through pumped storage schemes (Figures 4 and 5)

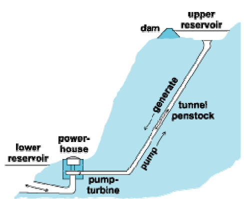

Fig. 4: Schematization of a pumped storage plant.

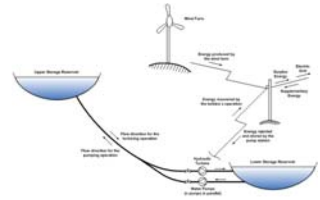

Fig. 4: A hybrid renewable energy system, combining hydroelectric and wind energy.

5. Scale issues in combined water and energy development

To fully exploit the hydroelectric projects, pumped storage plants should be applied on a large scale. As a form of energy, hydroelectricity is completely controllable if compared with the (highly uncertain) forms of wind and solar production. Moreover, the efficiency of hydropower reaches 95% for larger scale plants, while other forms hardly approach half of this value.

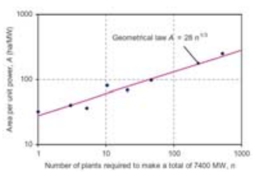

Fig. 5: reservoir area per unit power vs number of plants required to make a total of 7400 MW (Koutsoyiannis, 2011).

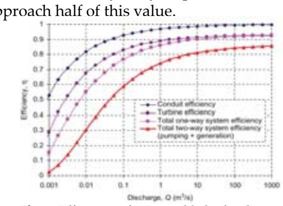

Fig. 6: Efficiency of a reversible hydroelectric project vs design discharge (Koutsoyiannis, 2011).

6. Modelling hybrid renewable energy systems

We provide a generalized formulation of the parameterization-simulation-optimization framework (Fig. 7), key concepts of which are:

- Generation of synthetic input series (inflows, wind velocity) via multivariate stochastic models;
- Low-dimensional representation of main system controls, through parsimonious parameterizations (e.g., operation rules);
- Faithful representation of the system dynamics, taking into account physical constraints, water and energy target priorities, and costs;
- Probabilistic assessment of all water and energy fluxes and quantification of uncertainties through Monte Carlo simulation;
- Use of multicriteria optimization to extract compromise solutions.

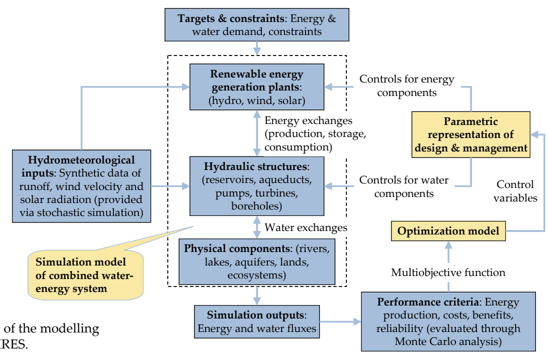

Fig. 7: Flowchart of the modelling framework for HRES.

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7. Study area

Aliakmon, located in Western Macedonia, is the longest river in Greece originating from Greek territory. Its headwater are the mountains Verno, Grammos and Voio, at the country's borders with Albania, and its estuaries are in the Aegean Sea, between Thessaloniki and Katerini. The river basin extends over five prefectures (Kastoria, Grevena, Kozani, Imathia, Pieria). The hydrosystem serves multiple and conflicting uses, i.e. water supply of Thessaloniki, irrigation of Western Macedonia district, cooling of Ptolemais Power Station, hydroelectric production and environmental flow.

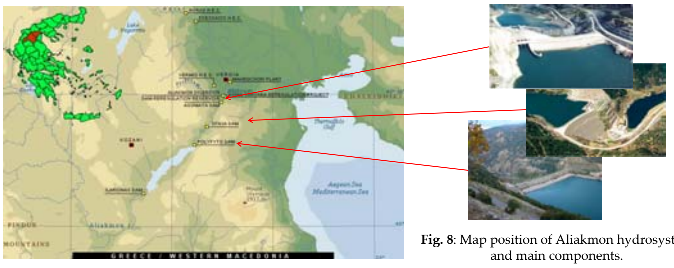


Fig. 8: Map position of Aliakmon hydrosystem and main components.

8. Layout of hypothetical HRES

The HRES consists of the real-world hydroelectric system and a hypothetical wind park (Fig. 9).

The **water resource system** is located in the middle course of Aliakmon river. It comprises three cascade hydroelectric reservoirs (Polyfyto, Sfikia, Asomata) and a pumped storage plant, between Sfikia and Asomata. As mentioned above, it also serves industrial, irrigation and environmental uses.

The **wind park** is assumed to be located in the same river basin, and comprises an unknown number of commercial wind turbines (7.5 MW; type E-126 by Enercon). The current scheme corresponds to the general methdodological framework described in Figure 7, by combining hydroelectric and wind energy in a pumped storage plant.

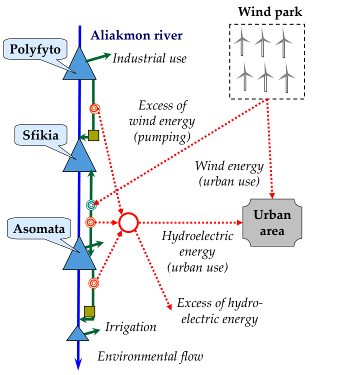


Fig .9: Layout of the hybrid system, in which are illustrated all water and energy fluxes.

9. Modelling of monthly operation of hydroelectric system

The decision support system **Hydronomeas** was used to optimize the monthly operation of the hydrosystem, assuming steady-state simulation of 1000-year horizon. We investigated two configurations, one without pumped storage (scenario S1) and one with the existing pumped storage plant between Sfikia and Asomata (scenario S2; Fig. 10). Synthetic series of inflows (runoff, rainfall) and losses (evaporation) at all reservoir locations were generated through **Castalia**, which employs a two-level (annual, monthly) multivariate stochastic model.

The common objective was the maximization of the total firm energy of the system, which was estimated on the basis of the sum of simulated energy by all hydropower plants that is available with 99% reliability. As shown in Fig. 11, the pumped storage system contributes to a major increase of the firm energy produced by the three hydropower plants.

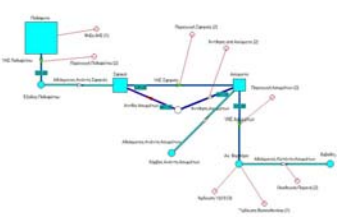


Fig. 10: Schematization of the Aliakmon hydrosystem in the graphical environment of Hydronomeas (scenario S2).

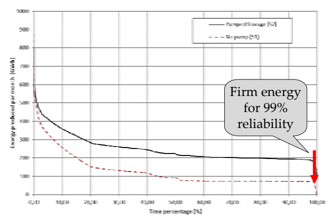


Fig. 11: Influence of pumped storage facility to the total energy production.

10. Modelling of daily operation of wind power system

We generated 1000 years of hourly wind speed data using a modified Bartlett-Lewis model implemented in **Hyetos**. Historical wind speed data were obtained from the meteorological station of Kilkis (Fig. 12). We note that Hyetos is typically employed for stochastic simulation of hourly rainfall, which key characteristic is **intermittency**, expressed in terms of probability dry (i.e. absence of rain). In this context, the model generates subsequent rainfall events instead of continuous time series. To overcome this characteristic, instead of original wind speed, w_t, we accounted for the speed above threshold w_0, i.e. $w_t^* = w_t - w_0$, where w_0 is the minimum required value for the activation of the wind turbine. On the basis of the power curve of the wind turbine, we calculated the hourly time series of wind energy, as function of simulated w_t (Fig. 13).

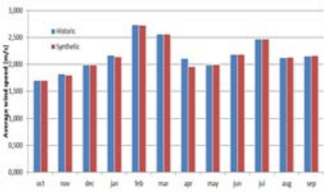


Fig. 12: Comparison of historical and simulated monthly mean values of w.

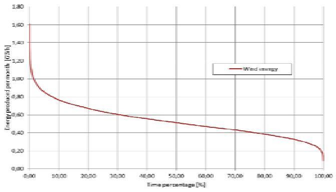
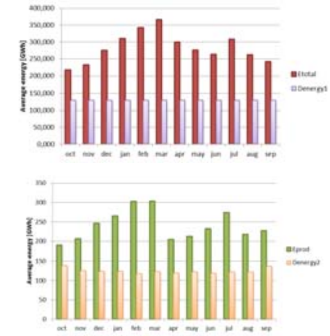


Fig. 13: Duration curve extracted from the simulated wind energy time series.

11. Model combination for optimal planning of HRES

We divided the day in two periods: the first one is the **production period** (high demand hours) and the second one the **pumping period**. The associated model configurations are shown in Fig. 14. During the first period, the total energy production is $E_1 = E_{tur}^* + \alpha\, \Pi_w$ while during the second (i.e. pumping) period it is $E_2 = (1 - \alpha)\, \Pi_w$. The **control variables** of the optimization problem are: the percentage of turbine operation α, the average daily demand D, the demand ratio b for the production period, such as $D_1 = b\, D$ and $D_1 = (1 - b)\, D$, and the number of wind turbines n. Our design framework was based on the **minimization** of the average deficit in **the two discrete periods** and the simultaneous **maximization** of the overall system **reliability**, in terms of covering the energy demand during the two periods.

The results of simulations, in terms of monthly means, as well as the key data for the two periods are shown in Fig. 15. The optimal values of the design variables are D = 150 GWh, b = 0.87, a = 0.40 and n = 750 turbines.



	Period 1	Period 2
Energy demand (GWh)	130	20
Average deficit (GWh)	0.00	1.05
Failure probability	0.05%	4.96%

Fig. 15: Optimal results for HRES planning.

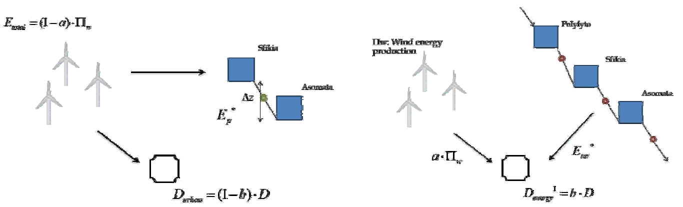


Fig. 14: Model configuration during the two demand periods (left: pumping period, right: production period).

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