A stochastic simulation framework for planning and management of combined hydropower and wind energy systems

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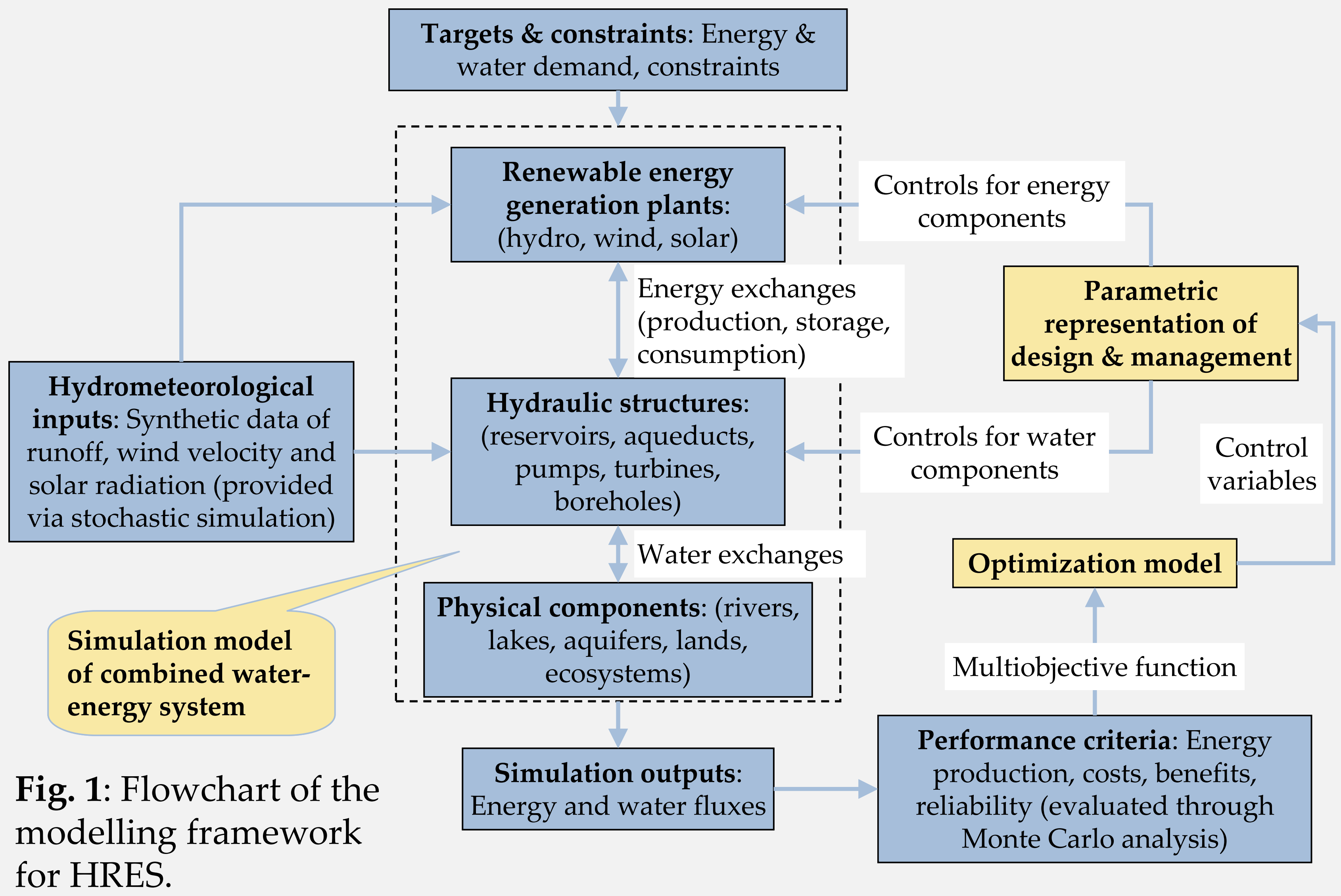
1. Abstract

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 energy (e.g. during night) and next retrieving this water to generate hydropower during demand peaks. This excess can be offered by other **renewables**, which can be integrated within hydroelectric systems with pumped storage facilities to formulate **autonomous hybrid renewable energy systems (HRES)**. The optimal planning and management of HRES requires a holistic overview, 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. Modelling hybrid renewable energy systems

We provide a generalized formulation of the parameterization-simulation-optimization framework (Fig. 1), key concepts of which are:

- Generation of synthetic input series (inflows, wind velocity) through multivariate stochastic models;
- Low-dimensional representation of the 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.



Targets & constraints: Energy & water demand, constraints

Renewable energy generation plants: (hydro, wind, solar)

Controls for energy components

Energy exchanges (production, storage, consumption)

Parametric representation of design & management

Hydrometeorological inputs: Synthetic data of runoff, wind velocity and solar radiation (provided via stochastic simulation)

Hydraulic structures: (reservoirs, aqueducts, pumps, turbines, boreholes)

Controls for water components

Control variables

Water exchanges

Optimization model

Simulation model of combined water-energy system

Physical components: (rivers, lakes, aquifers, lands, ecosystems)

Multiobjective function

Simulation outputs: Energy and water fluxes

Performance criteria: Energy production, costs, benefits, reliability (evaluated through Monte Carlo analysis)

Fig. 1: Flowchart of the modelling framework for HRES.

3. Layout of the hybrid system in study

The HRES consists of a real-world hydroelectric system and a hypothetical wind park (Fig. 2).

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

The **wind park** is assumed to be located in the same basin, and comprises an unknown number of commercial wind turbines (7.5 MW; type E-126 by Enercon).

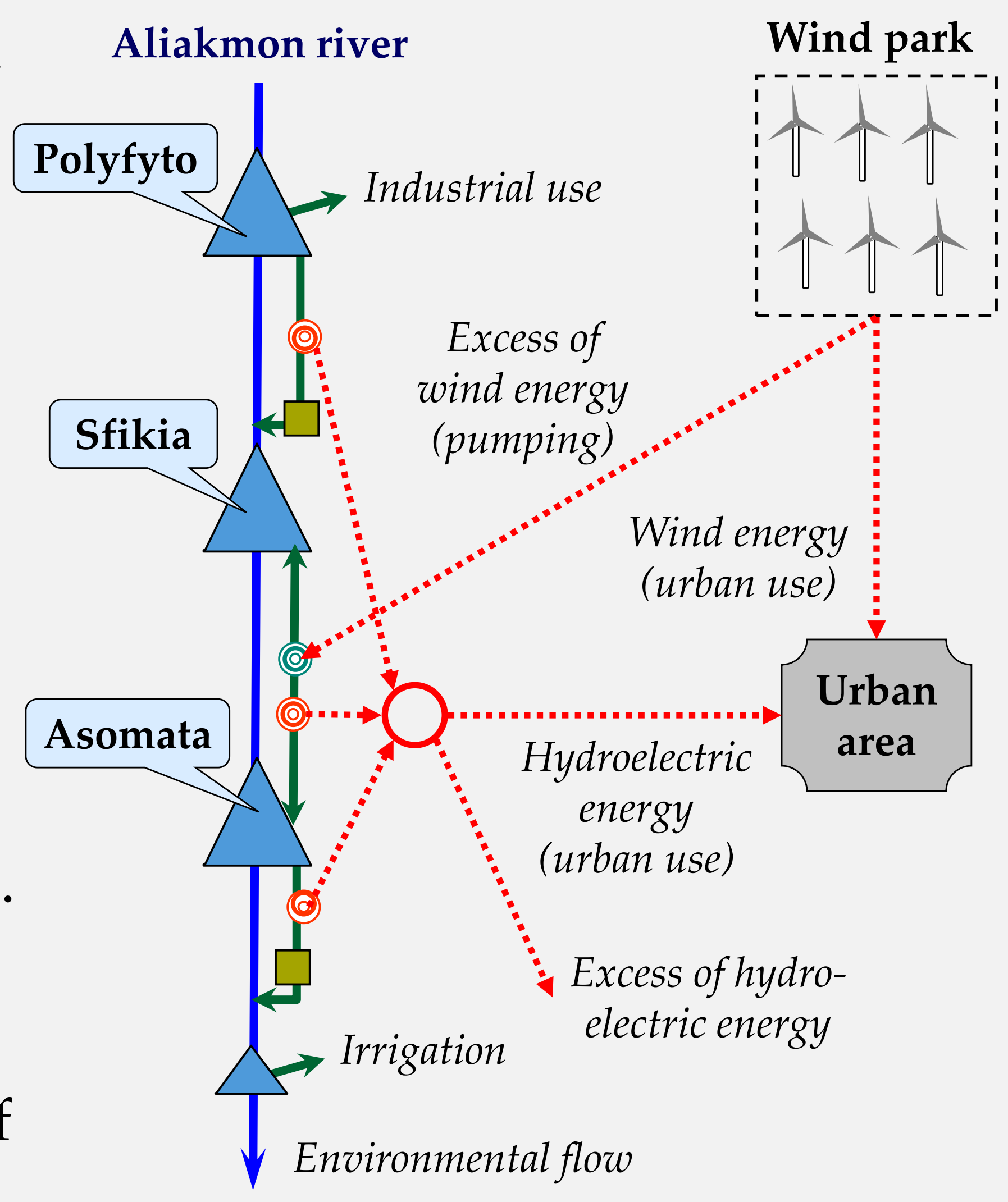


Fig .2: Layout of the hybrid system, showing all water and energy fluxes.

4. Optimization of Aliakmon hydrosystem

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. 3).

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. 4, the pumped storage system contributes to a major increase of the firm energy produced by the three hydropower plants.

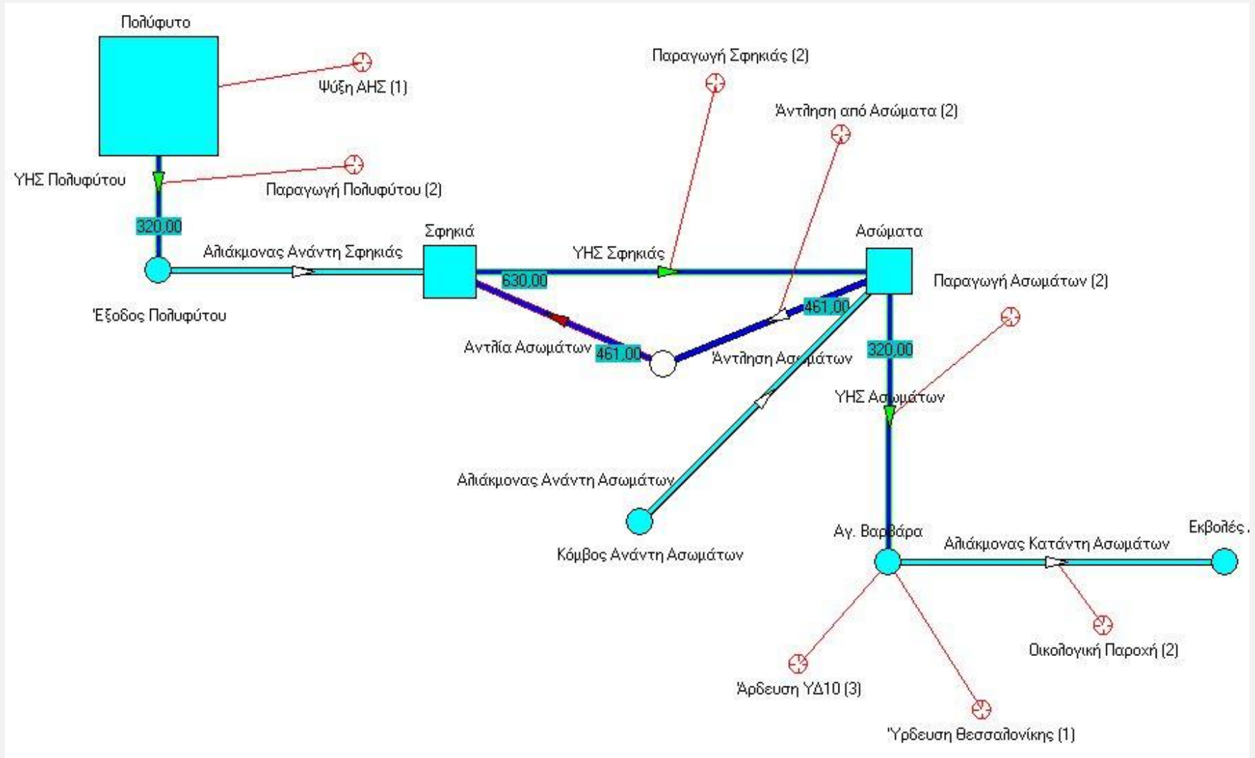
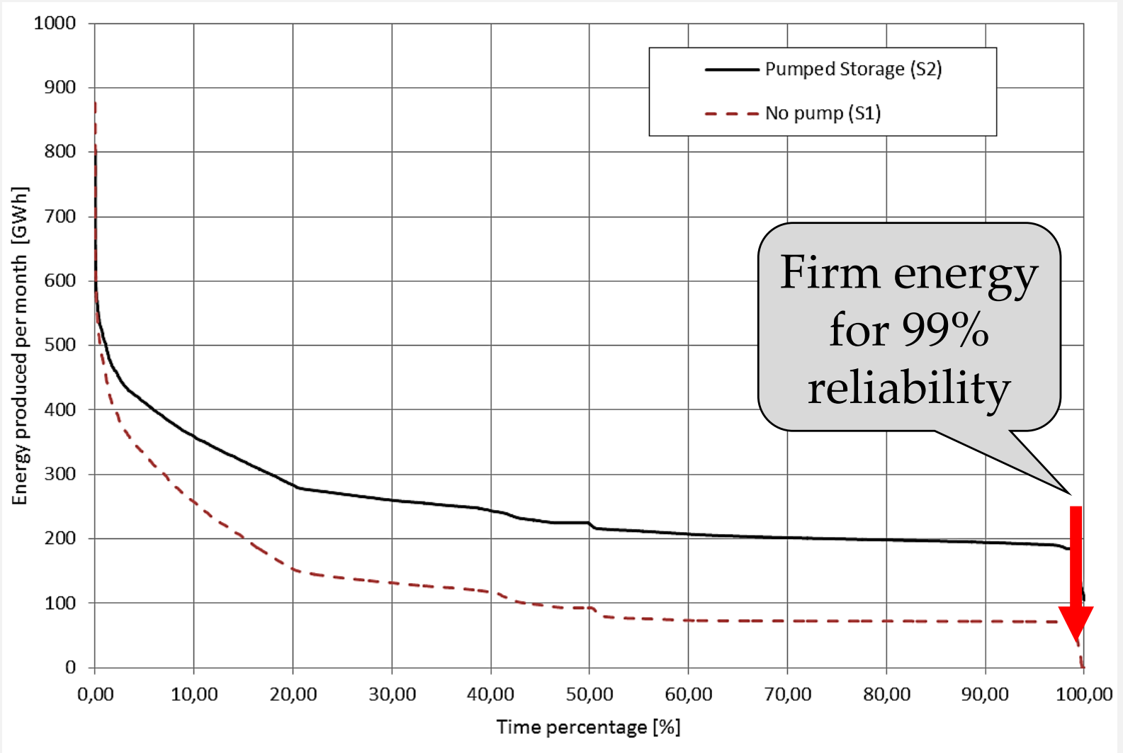


Fig. 3: Layout of the Aliakmon hydrosystem in Hydronomeas (scenario S2).



Firm energy for 99% reliability

Fig. 4: Influence of pumped storage facility to the total energy production.

5. Simulation of wind energy production

We generated 1000 years of hourly wind speed data using a modified Bartlett-Lewis model implemented in **Hyetos**. Historical wind speed data was obtained from the meteorological station of Kilkis (Fig. 5). 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. 6).

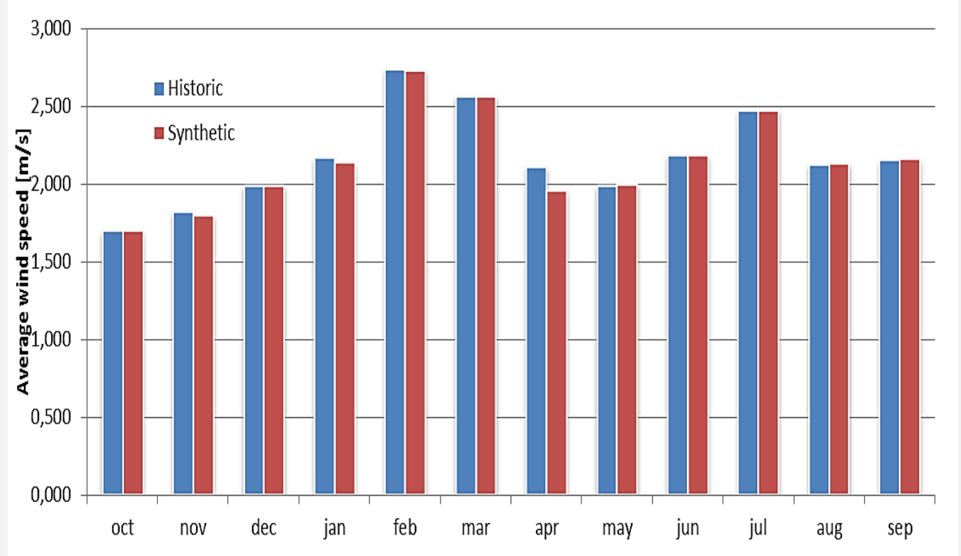


Fig. 5: Comparison of historical and simulated monthly mean values of w.

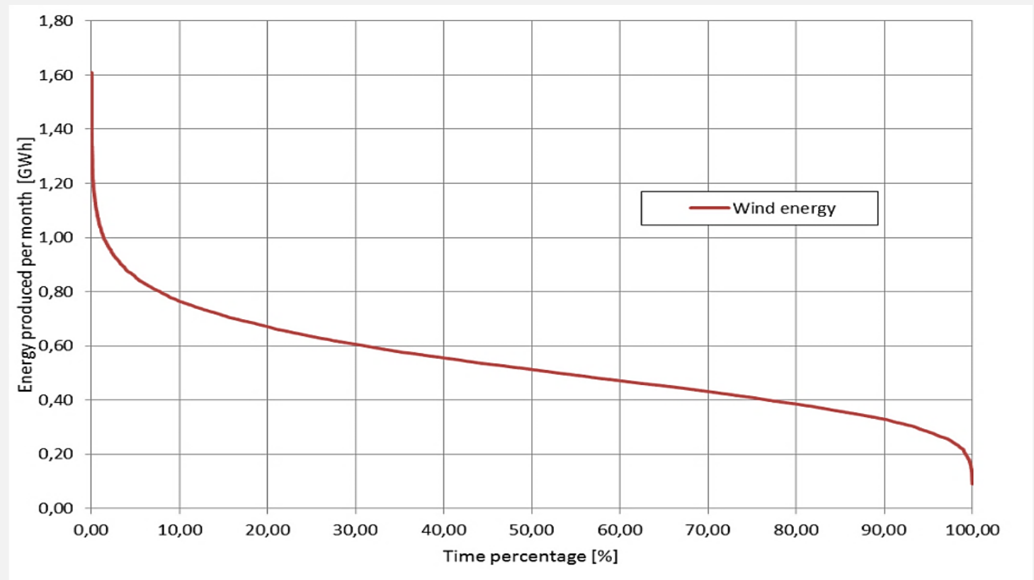


Fig. 6: Duration curves extracted from the simulated wind energy time series.

6. Optimal planning of HRES

Assuming constant energy demand D_A, we determined the number of wind turbines and the pumping duration (i.e., percentage of pumping hours per day), by comparing, on mean monthly basis, the excess of wind energy production, E_P, with the pumping energy potential, E_P^* (i.e., simulated energy consumption by the pumped storage unit).

As shown in Fig. 7, E_P^* is practically constant while E_P follows the **variability of wind**. Moreover, small portion of the hydroelectric production, E_tur^*, is used to fulfill the energy deficits, ΔD_A, in the urban area. In an operational context, this indicates that the management of the hydrosystem must be adapted to the running meteorological conditions. For, this is feasible grace to the **large scale** of reservoirs and the **flexibility** of the pumps and turbines.

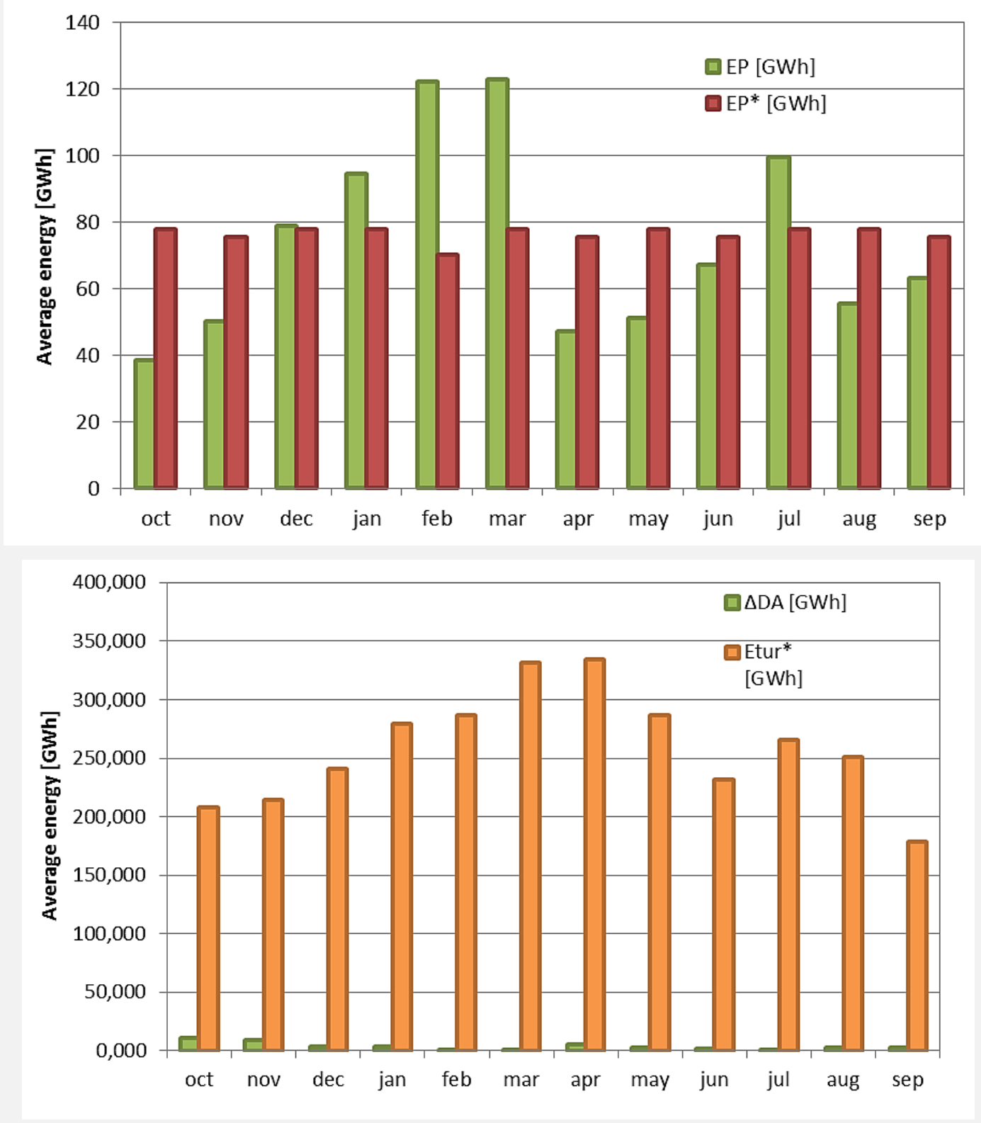


Fig. 7: Excess of wind energy production vs. pumping energy potential (up) and energy deficit vs. hydroelectric production (down), on mean monthly basis.