A stochastic simulation framework for representing water, energy and financial fluxes across a non-connected island

EGU General Assembly 2019, Vienna, Austria, 7-12 April 2019; Session HS5.3.1/ERE2.8: *Advances in modeling and control of environmental systems: from drainage and irrigation to hybrid energy generation*

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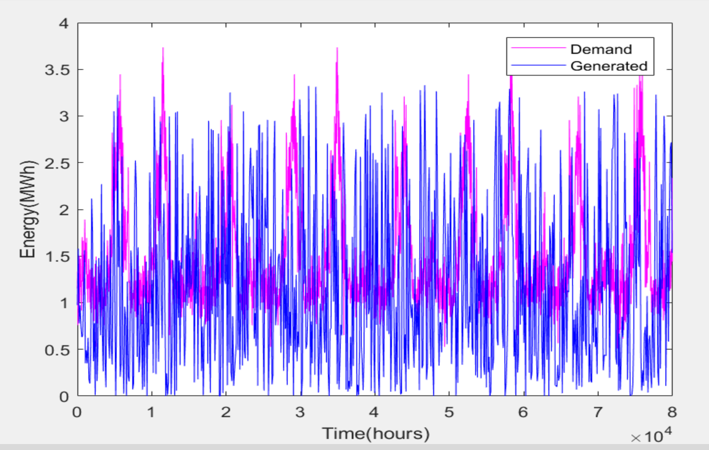
1. Abstract

Integrated modeling of hybrid water-energy systems, comprising conventional and renewable energy sources, pumped-storage facilities and other infrastructures, which aim to serve **combined water and energy uses**, is a highly challenging problem. On the one hand, such systems are subject to significant **uncertainties** that span over all associated input processes, **physical and anthropogenic** (i.e., hydrometeorological drivers and water-energy demands, respectively). On the other hand, the everyday operation of such systems is subject to multiple **complexities**, due to the conflicting uses, constraints and economic interests. Taking as example a future configuration of the electric system of Ikaria Island, Greece, we demonstrate a **stochastic simulation framework**, comprising: (a) a **synthetic time series generator** that reproduces the statistical and stochastic properties (i.e., marginal distributions, auto- and cross-dependencies) of all input processes, at multiple temporal scales; and (b) a simulation module employing the **hourly operation of the system**, to estimate the associated water, energy and financial fluxes. This scheme is used within two case studies, i.e. **the optimal design** of key system components, and the **real-time operation of a hypothetical energy market**, involving different energy providers and associated electricity sources, conventional and renewable.

2. Rationale of hybrid energy systems

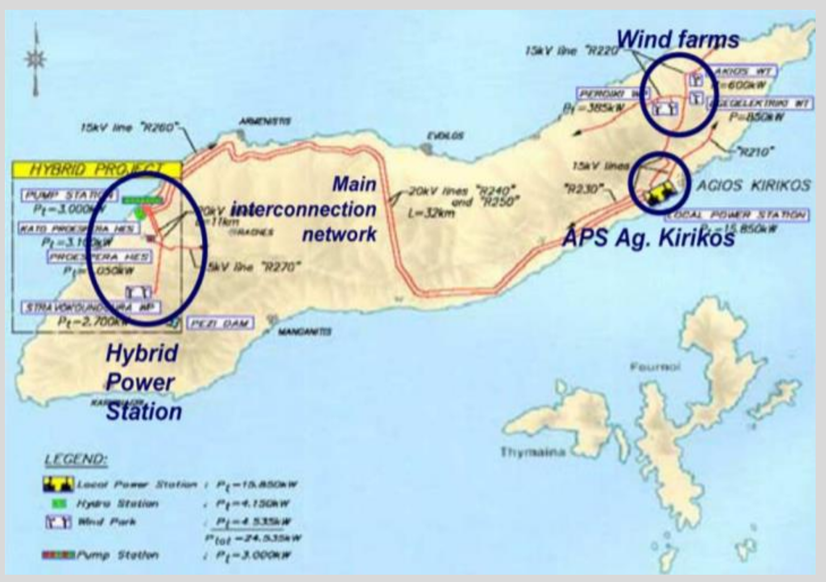
- Due to the stochastic regime of weather conditions, standalone wind energy systems are highly unreliable, resulting to **energy surpluses and deficits**.
- The combination of wind units with **pumped energy storage** is considered the most effective means to significantly increase the penetration of wind energy within electric power systems, particularly in small autonomous island grids, where several technical limitations are imposed by the conventional energy units.
- The aim of hybrid systems is to **synchronize** the energy offered by different sources with demand, in order to maximize the efficiency of power production.
- When the wind production exceeds the demand, water is pumped from a lower to an upper water storage component (tank or reservoir), to **store surplus wind energy as hydrodynamic energy**.
- Typically, energy surpluses occur during **late night hours** and the **winter** period, when the power demand is relatively low.
- In contrast, when the wind energy production cannot fulfil the demand, water is released from the upper reservoir, to fulfil the **energy deficit as hydropower**.



3. Case study: Wind-hydro-pumped storage system in the autonomous island of Ikaria, Eastern Aegean, Greece

Summary information:

- Total extent 255 km²
- 8 423 residents (2011 nexus);
- Summer population: 20 000 people (approximation);
- Mostly mountainous relief (max. elevation 1051 m);
- Cultivated land in the NW; annual water demand for irrigation 450 000 m³.
- Mild climate, strong summer winds, called "Meltemia".



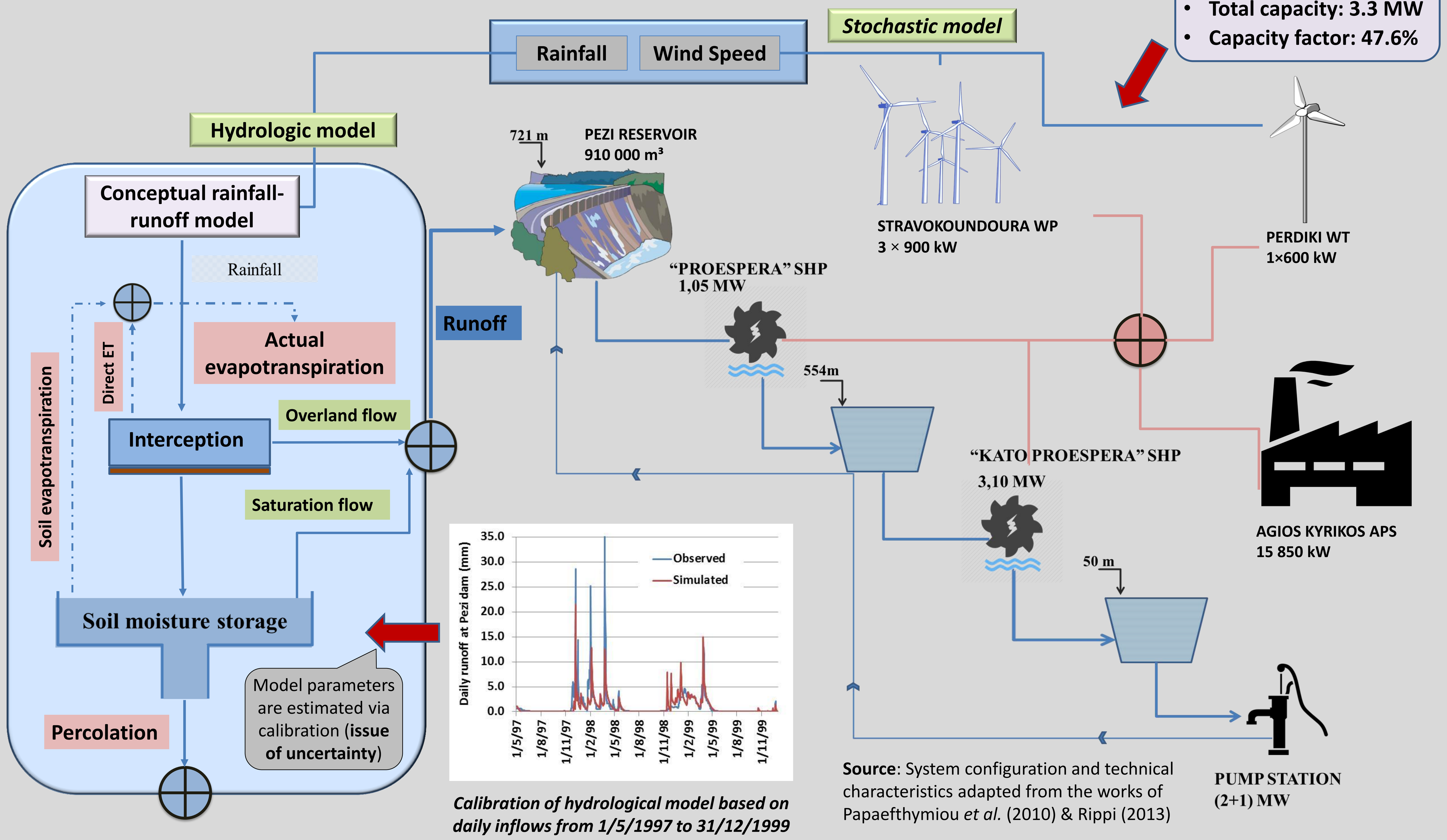
Components of hybrid water-energy system:

- Existing diesel power station in Agios Kirikos (est. 1967);
- Three interconnected water storage elements, i.e. Pezi reservoir (est. 1990; total capacity 910 000 m³, fulfill most of irrigation and small portion of drinking water demands), and two small tanks under construction, in Proespera and Kato (Lower) Proespera (each one of 60 000 m³) ;
- Two small hydropower stations in the route Pezi-Proespera-Kato Proespera.
- Pumping station lifting water from Kato Proespera to Proespera (3.0 MW);
- Wind farm in Stravokountoura, comprising three wind turbines (2.7 MW), and isolated wind turbine in Perdiki (0.6 MW);
- Control center and dispatching of load in Agios Kirikos.

Ikaria is one of Aegean islands with the **largest wind potential**, since the annual average wind speed at the mean elevation of the island is estimated up to 7.5 m/s.

4. Outline of water-energy simulation procedure: data, models, parameters & processes

Wind farm characteristics
- **Total capacity: 3.3 MW**
- **Capacity factor: 47.6%**



Calibration of hydrological model based on daily inflows from 1/5/1997 to 31/12/1999

Source: System configuration and technical characteristics adapted from the works of Papaefthymiou *et al.* (2010) & Rippi (2013)

Key outcomes of preliminary analyses

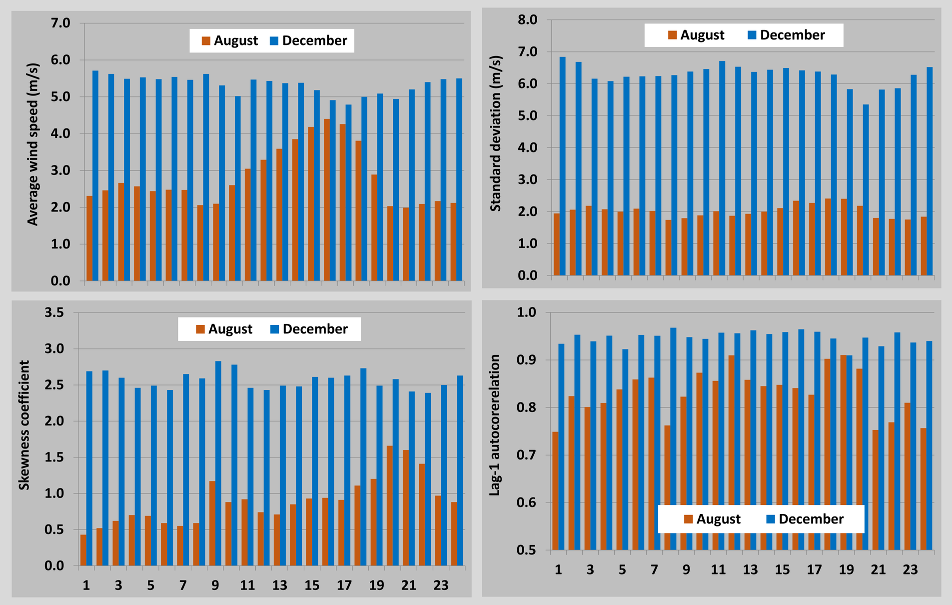
Without the APS
- **Energy production reliability: 66%**
- **Deficit vulnerability: 0.93 MWh**
- **Irrigation reliability: 93.3%**
- **Deficit vulnerability: 107.2 m³**

Without the hybrid system
- **55% of energy production can meet the power demand**
- **up to 6250 MWh per year will not be exploited (energy excess)**

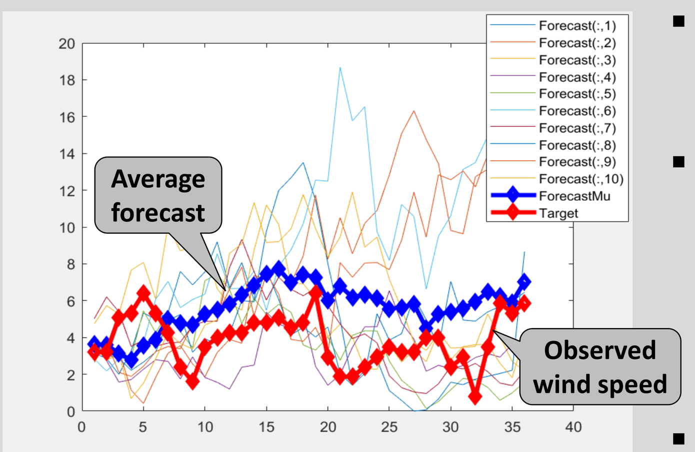
Key research challenge is the simulation of a hypothetically free energy market, involving three energy providers:
- **Wind Farm (WF)**
- **Hydroelectric Power Station (HPS)**
- **Autonomous Power Station (APS)**

5. Stochastic simulation and forecasting of hourly wind speed

- The wind speed process at fine time scales (e.g., hourly) is characterized by major peculiarities, since its statistical behavior changes both across seasons (months) and the daily cycle (an attribute referred to as **double periodicity**; cf. Dimitriadis & Koutsoyiannis, 2015).
- Statistical analysis of hourly wind data from Ikaria (2012-2018) also revealed the existence of intermittency, asymmetry and strong dependence across consecutive hours.
- These data were used within a novel stochastic approach, named **Stochastic Periodic Auto-Regressive to Anything (SPARTA)**, for generating 50 years of hourly synthetic time series, next used as inputs in water-energy simulations (Tsoukalas *et al.*, 2018a, b; Tsoukalas, 2018).
- Main advantages of SPARTA are the preservation of double periodicity (cyclostationarity), by allowing to fit **any distribution model** to represent the **individual statistical regime of each hour of each month**, and the generation of **realistic dependence patterns**.
- To describe the **intermittent** nature of wind, zero-inflated (i.e., mixed) distributions with Generalized Gamma and Burr type-XII were used for representing non-zero wind speed.



Plots of intra-daily (i.e., hourly) statistical characteristics of wind speed data at Ikaria for two characteristics months (August, December)



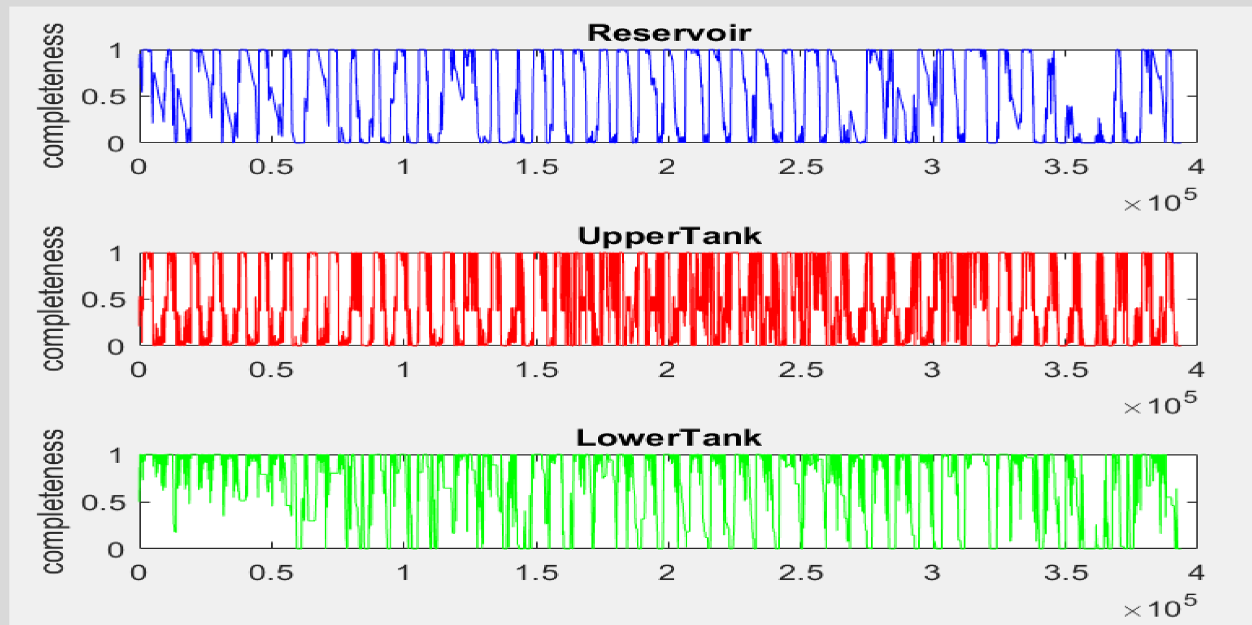
Example of ten forecast sets of wind speed for 36 hours lead time, by combining SPARTA with KNN

- For real-time energy market simulations, we developed an innovative **forecasting procedure**, to provide stochastic projections of the upcoming wind speeds up to 36 hours lead time, by running each day at 12:00 am (t_0) and estimating the upcoming wind speed from time step $t_0 + 12$ up to $t_0 + 36$ (hours).
- Initially, we employed **SPARTA** for generating 1000 years of synthetic hourly wind speed data, which were next used as input for a **K-Nearest Neighbors Algorithm** (KNN). The latter simply stores a **collection of examples**, each one comprising a vector of features (describing the example) and its associated class (for classification) or numeric value (for prediction). Given a new example, KNN finds its *k* most similar examples (called nearest neighbors), according to a distance metric, and predicts its class as the majority class of its nearest neighbors or, in the case of regression, as an aggregation of the target values associated with its nearest neighbors.
- This scheme was repeated to provide ten realizations of hourly wind speed, for the entire simulation horizon.

Acknowledgments: We are grateful to Dr. Vassiliki Kotroni and Dr. Kostas Lagouvardos, National Observatory of Athens, for kindly providing historical wind data from the automatic meteorological station at Raches, Ikaria (http://penteli.meteo.gr/stations/ikaria/).

6. Real-time energy market simulation in a nutshell

- The **energy auction** regarding the next 24 hours takes place daily, at t_0 =12:00 am.
- Firstly, the wind speed and the demand of energy for time step $t_0 + 12$ until $t_0 + 36$ are estimated by the aforementioned forecasting process and then the three players make their offers against the projected energy demand (24 hourly values).
- The offer of the **Wind Farm** (WF) accounts for the forecasted energy and aims at least to the depreciation of the investment. When strong winds are expected, the WF is considered to be the **most competitive player**. The penalty that is imposed to the WF, if it does not generate the promised amount of energy, is relatively low, in order to **favor renewable sources** that are inherently highly uncertain.
- The criteria of the configuration of the **Hydroelectric Power Station** (HPS) offer are the **completeness of the reservoir and the upper tank** and the **seasonally-varying restrictions** that are imposed due to irrigation demands. The offers of HPS are generally higher than the ones of WF.
- Under some premise, e.g., during the winter and under high water storage, HPS is allowed to offer **lower prices** than WF, in order to enter the market and gain from the surplus of energy provided the other two players, through pumped-storage.
- In general, the configuration of the HPS offer is remarkably difficult due to the plethora of factors concerning its availability and the relatively high penalty that is imposed in case of deficits.
- The offer of the **Autonomous Power Station** (APS) is significantly higher than the other ones, owning to the cost of the oil transport and environmental taxes.
- Mostly, the energy demand is fulfilled by the WF and HPS, thus leaving to the APS the role of covering the deficits, in order to **maintain the reliability at 100%**.
- Since for technical reasons the operation of APS can not be terminated, energy surpluses are quite often and they are regulated by the pumped-storage system.



7. Conclusions & future research perspectives

- **High exploitation of renewable energy production** due to flexibility offered by the hybrid system (storage of excess energy), which allows regulating the **stochastic behaviour** of input meteorological processes;
- **Elimination of risks of energy deficits**, at the same time ensuring energy production in lower prices than today (monopoly of diesel station);
- Fulfilment of **irrigation demand** with high reliability;
- Future research will be focused on:
  - Improving forecasts by coupling stochastic and deterministic approaches;
  - Optimizing the energy market model to find a win-win equilibrium for all energy providers and the consumers.

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