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ERE2.4 – Pumped Hydropower Storage and Energy System Modelling

Driving energy systems with synthetic electricity prices

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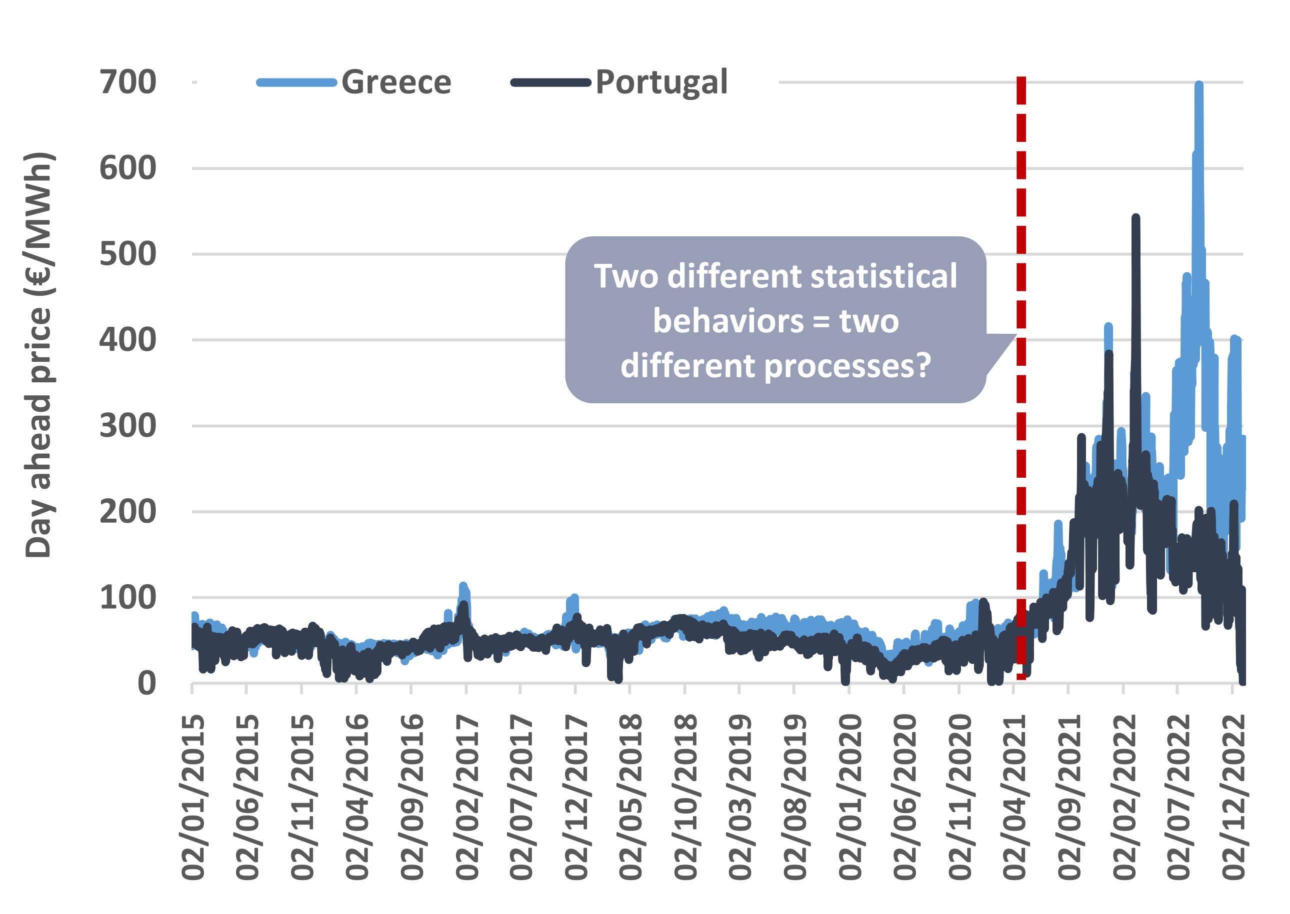
The challenge of generating synthetic electricity prices

- Electricity market prices are major drivers of the **planning**, **design, strategic management and real-time operation** of energy systems, also including the water-energy-food nexus (Sakki *et al.*, 2022).
- The energy market dynamics can be modelled in **stochastic** means (e.g., Hou *et al.*, 2017), by considering electricity prices as **random processes** that follow the **probabilistic regime** and **dependence structure** of historical data.
- Typical use of stochastic models is providing **synthetic data** to support **forecasting** or **long-term simulation** studies (here emphasis is put on *simulation*).
- Since the present structure of energy markets under the Target Model renders them strongly dependent on **socioeconomic disturbances** and **highly unpredictable events** (financial, geopolitical & health crises), challenging issues to account for within the data synthesis procedure are:
  - the representation of inherent peculiarities of electricity market process, such as **volatility**, **spikes**, and **periodicities** across seasons, weeks and the intraday cycle;
  - the **limited statistical information** under the Target Model structure;
  - the need to produce **abnormal yet persistent shifts**, as observed during the recent energy crisis.

Cases of Greece and Portugal

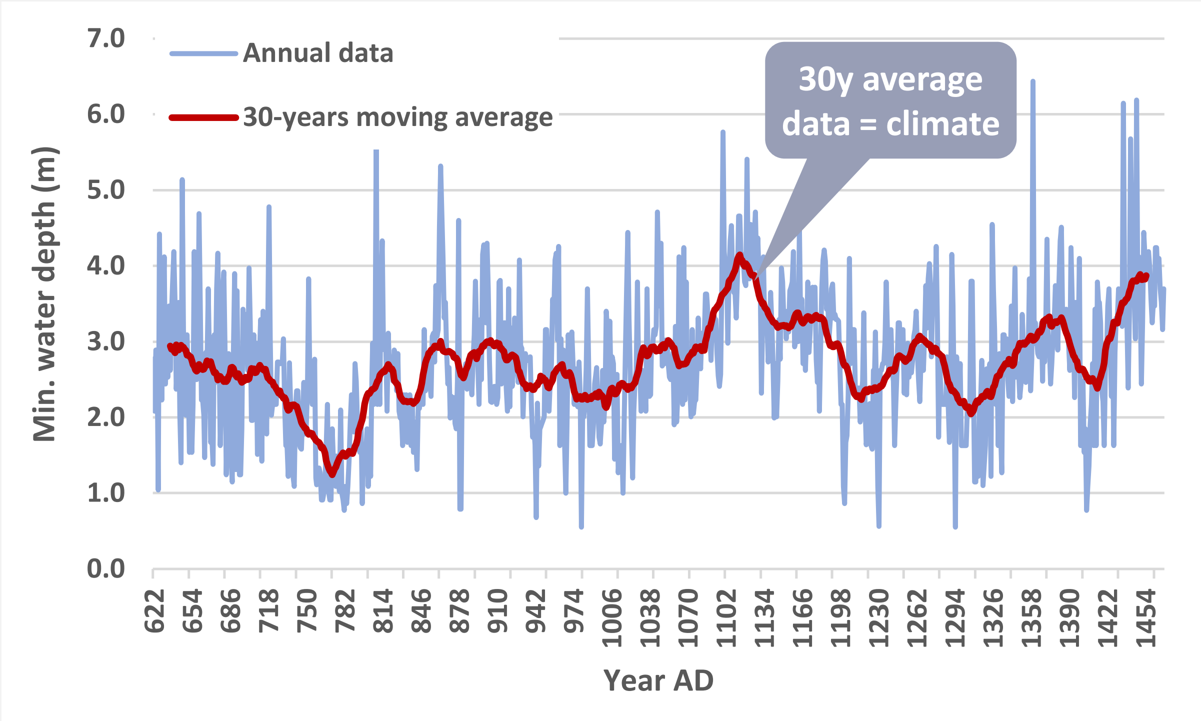
- Mediterranean countries with similar economic conditions, fiscal compliance, and financial sector development.
- Quite similar **energy mix**, strongly relying on imported gas, with significant contribution of renewables (hydro, solar, wind).

Electricity source	Greece (%)	Portugal (%)
Coal	10.4	0.1
Oil	9.0	3.1
Gas	37.3	37.0
Hydropower	9.0	16.2
Solar	12.6	6.5
Wind	20.7	28.3
Bioenergy	1.0	8.5
Other renewables	0.0	0.4



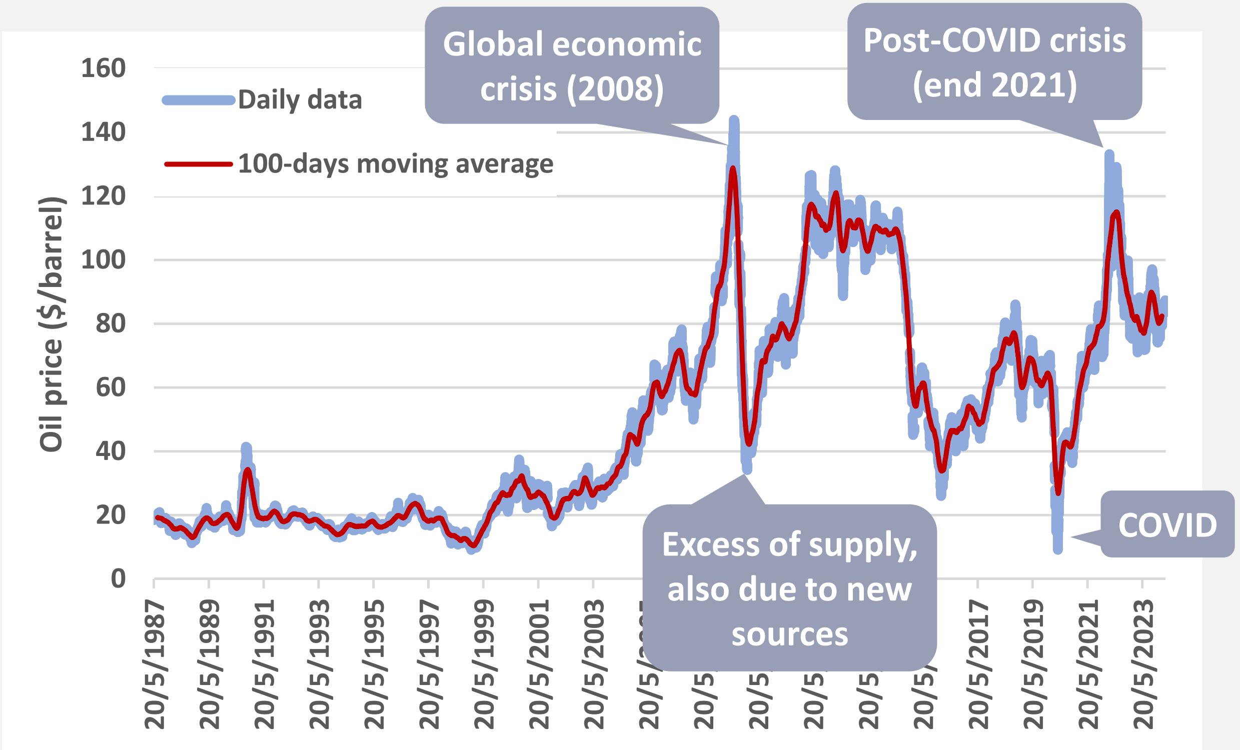
*Day-ahead market prices, retrieved by the ENTSO-E platform (from 1/1/2015 to 31/12/2022). **Is it possible to represent their irregular dynamics through a stochastic stationary model?***

Long-term persistence: A common aspect of physical & social processes



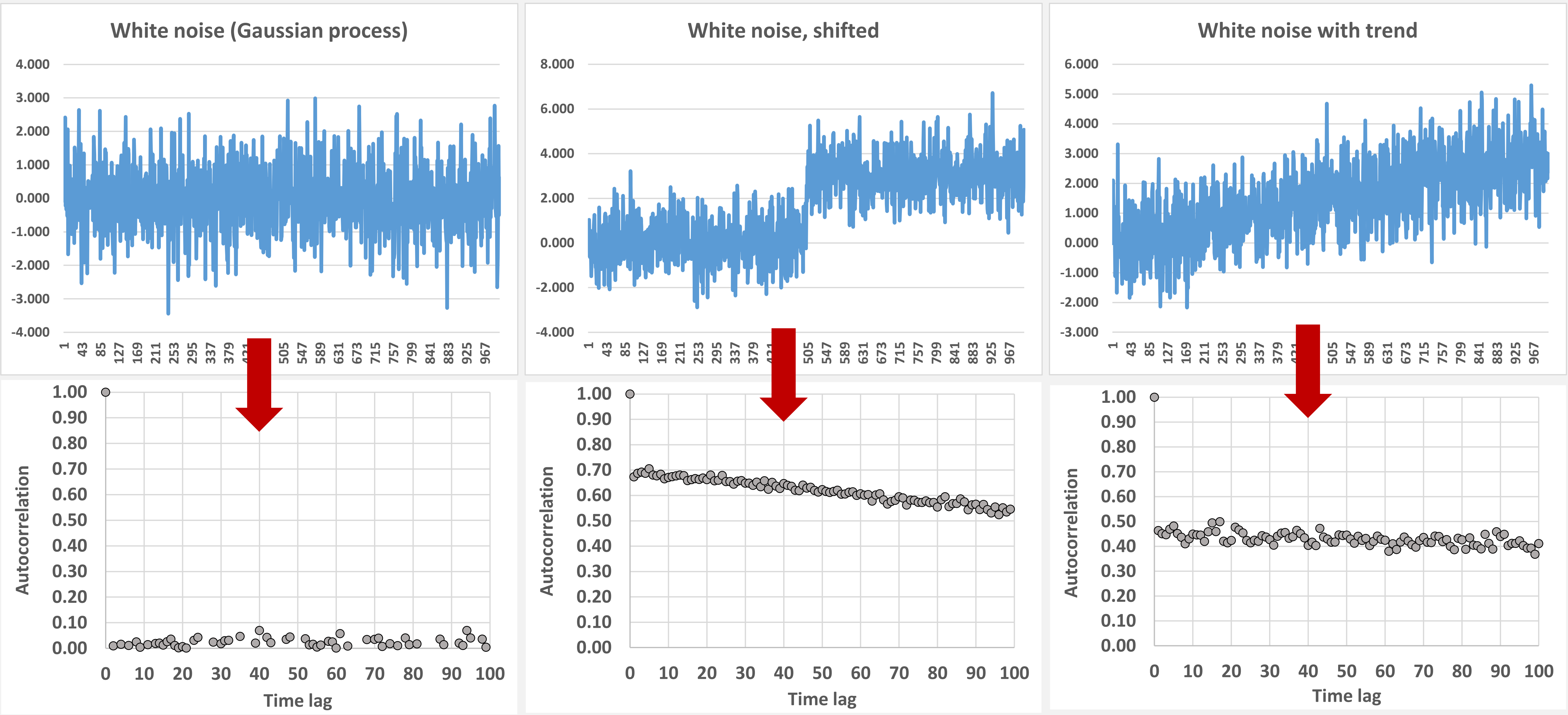
Nile River annual minimum water depth at Roda Nilometer *(retrieved by Koutsoyiannis, 2013). The Nile's behavior, first detected by H.E. Hurst (1951), has been a benchmark for hydrological sciences, highlighting that long-term persistence (LTP) is an* ***intrinsic property of geophysics and the climate****.*

LTP is also omnipresent in complex socioeconomic processes that drive the evolution of markets & commodities, e.g., ***crude oil prices****. Shifts, trends and long-range fluctuations are footprints of a* ***perpetually changing*** *world, dominated by LTP (also referred to as Hurst-Kolmogorov dynamics; Koutsoyiannis, 2011).*



Hint: LTP is easily formalized in stochastic means, by assigning "heavy-tailed" auto-dependence structures.

Mind the autocorrelations!



The stochastic modelling framework in a nutshell

- Remove of seasonality through **data standardization**, i.e., $x_t^* = (x_t - \mu)/\sigma$ (where μ and σ the sample mean and standard deviation values of the corresponding month), thus allowing to handle the process as **stationary**.
- Application of **Symmetric Moving Average (neaRly) To Anything** (SMARTA) scheme to standardized data (Tsoukalas et al., 2018), comprising three major modelling elements:
  - the **theoretical autocovariance function** (ACF), introduced by Koutsoyiannis (2000), allowing for reproducing a wide range of time-dependence structures (including LTP; Efstratiadis *et al.*, 2014);
  - the **Symmetric Moving Average** (SMA) generation procedure, as formalized by Koutsoyiannis (2000), to be aligned with the ACF;
  - the **Nataf's joint distribution model** (Nataf, 1962), which is related with the Gaussian copula, and enables the explicit representation of the process of interest with any distribution model.
- Model configuration (i.e., ACF assignment and distribution fitting), and eventually data synthesis, are facilitated through the **anySim package**, offering a suite of statistical and stochastic tools in R environment (Tsoukalas et al., 2020).

Mathematical background

- Assignment of a power-type **theoretical autocovariance function** (ACF):

$$\gamma_i = \gamma_0[1 + \kappa\,\beta\,i]^{-1/\beta}$$

where γ_i is the autocovariance of the process for lag i, γ_0 is the variance and κ, β are shape and scale parameters, respectively, that are related to the persistence of the process of interest (ARMA-type, for $\beta = 0$, more persistent structures, as β increases).

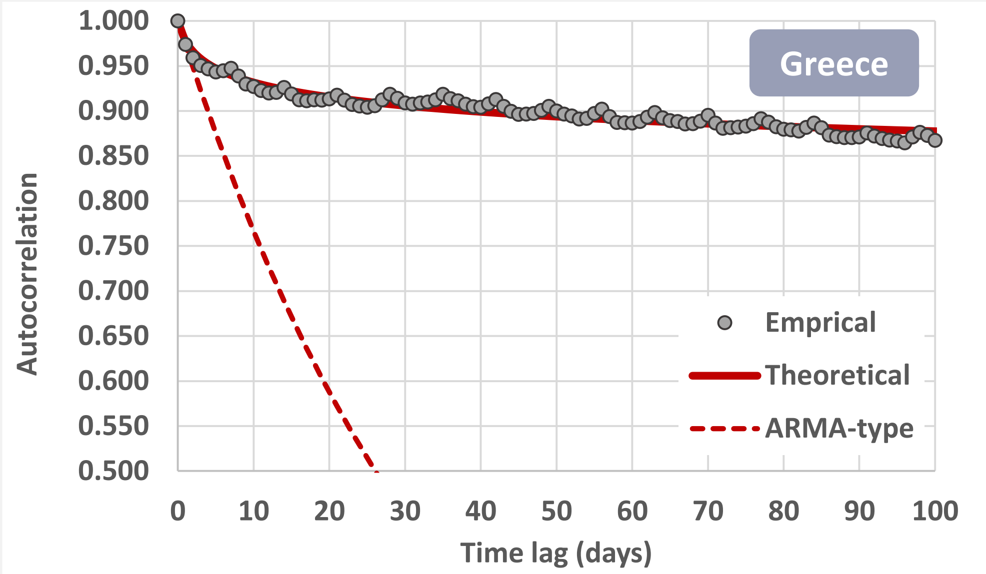
- Following the SMA rationale, we consider an auxiliary stochastic process $\underline{z}_i$, expressed as:

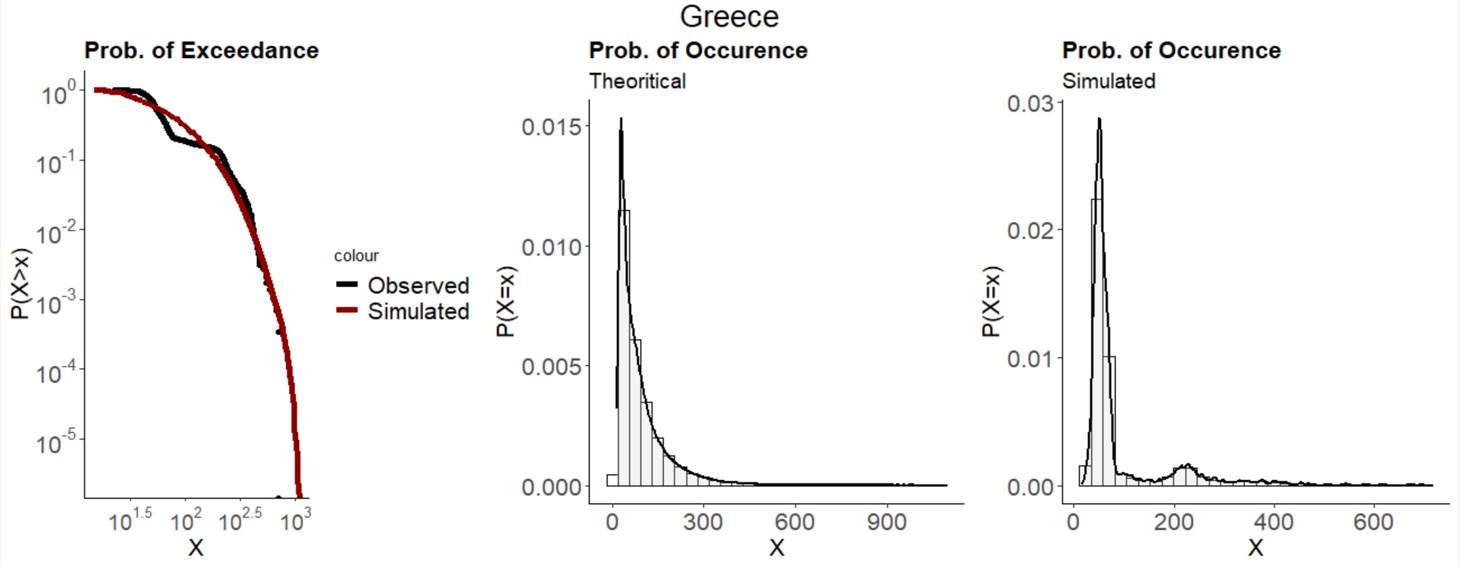
$$\underline{z}_i = \sum_{j=-q}^{q} a_{|j|}\,\underline{v}_{i+j} = \sum_{j=-q}^{q} a_s\,\underline{v}_{i-s} + \cdots + a_1\underline{v}_{i-1} + a_0\underline{v}_i + a_1\underline{v}_{i+1} + \cdots + a_s\underline{v}_{i+s}$$

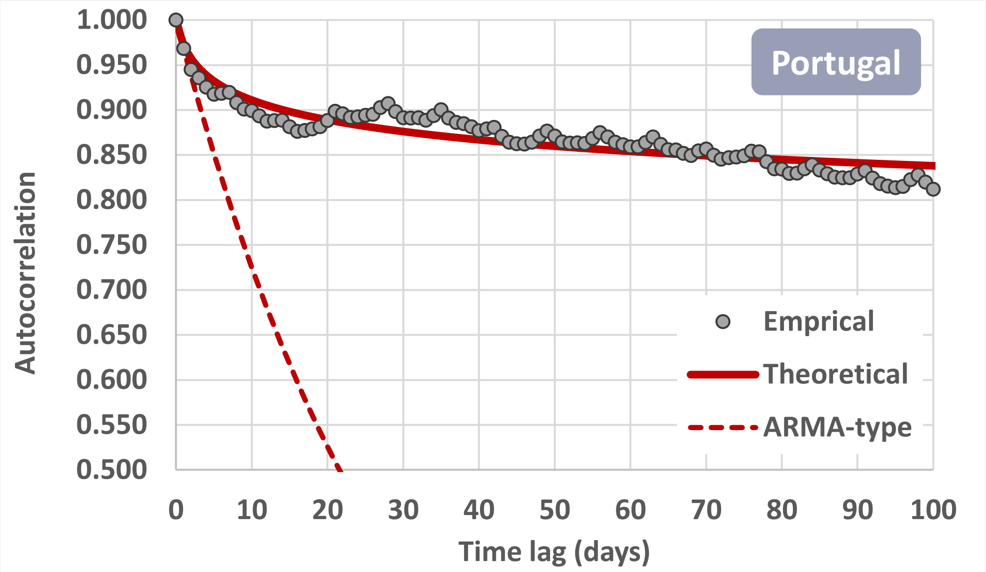
where $\underline{v}_i$ are noise variables that are generated from a Gaussian distribution, and a_j are weighting coefficients (symmetric), which can be **analytically determined from the sequence of $\boldsymbol{\gamma_j}$**.

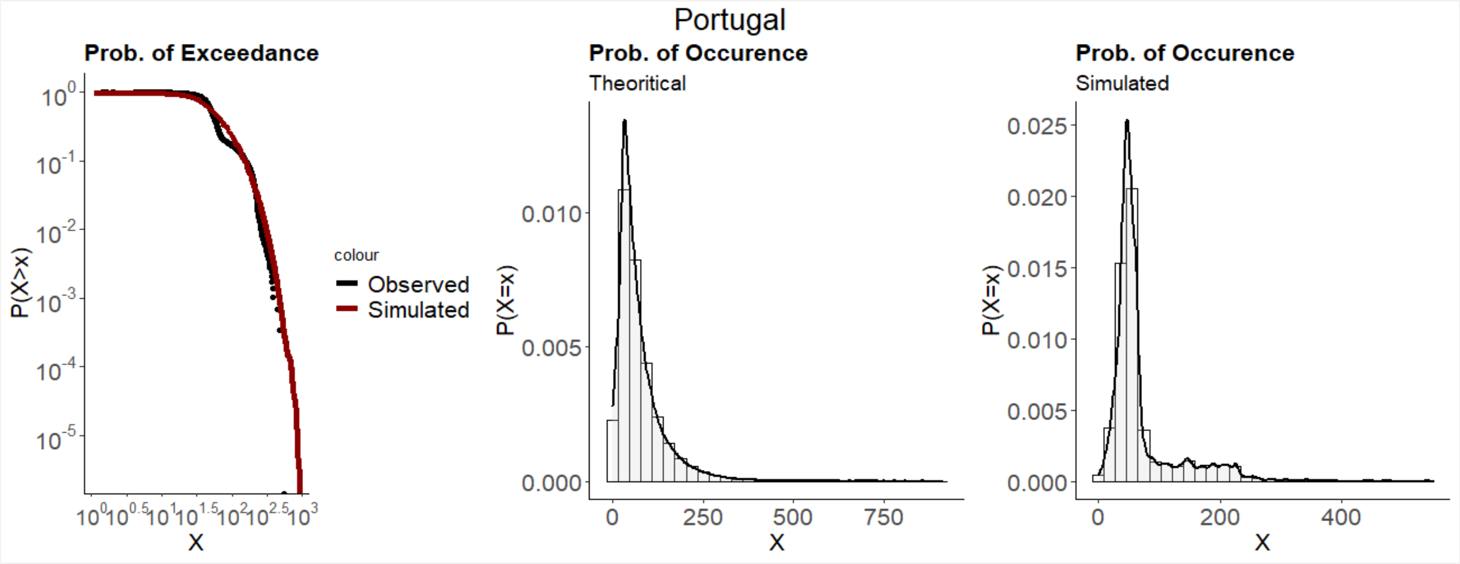
- Prior to parameters a_j, we identify the equivalent autocorrelations that result to the target ones (as specified via the theoretical ACF), after mapping of the Gaussian auxiliary process, $\underline{z}_i$, to the actual domain, $\underline{x}_i$ (i.e., the real process, to which a specific distribution model is assigned).

Fitting of autocorrelation functions & marginal distributions

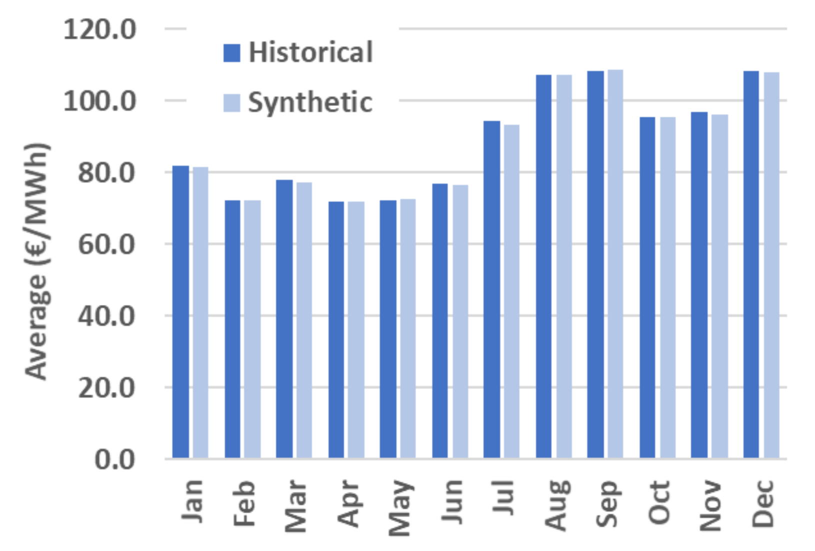


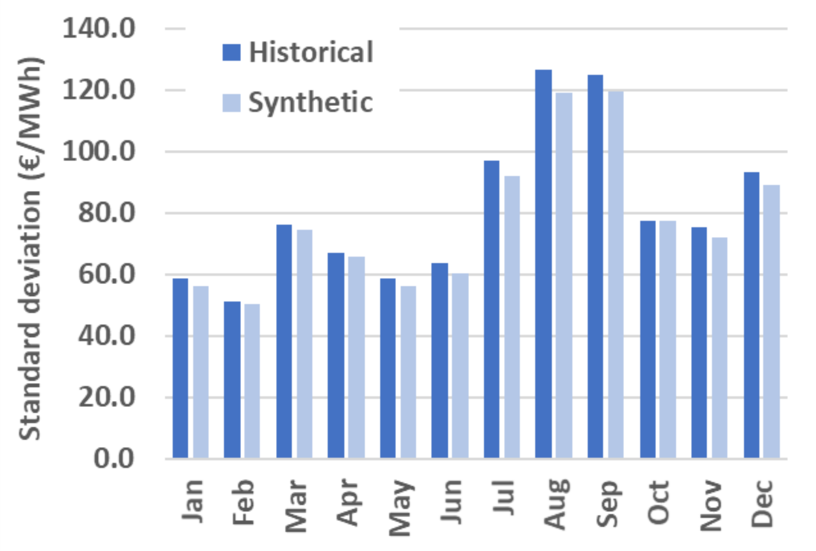


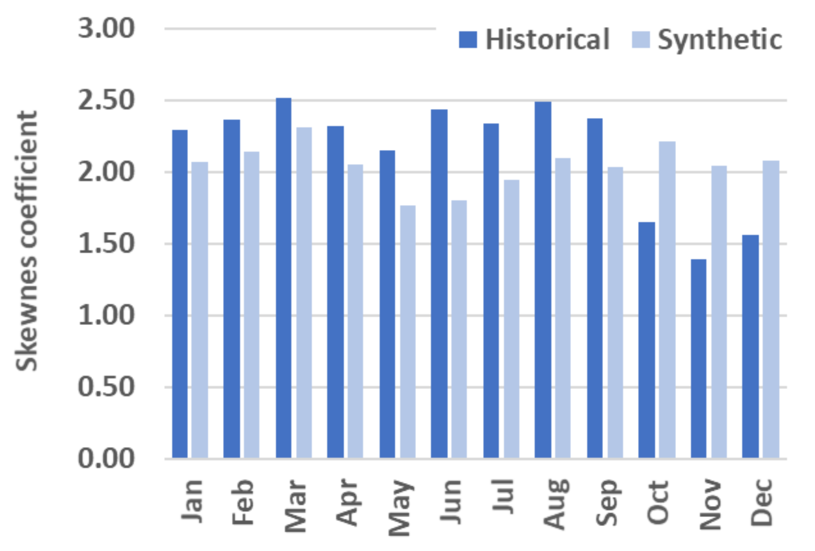


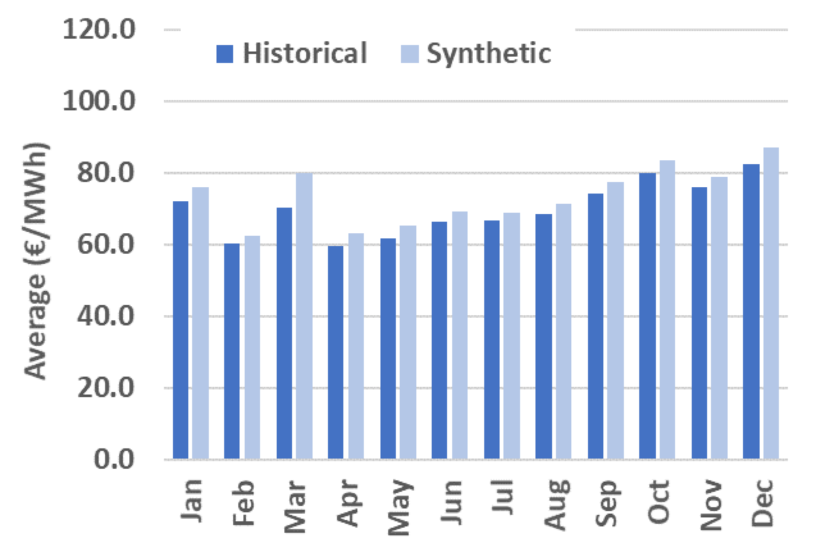


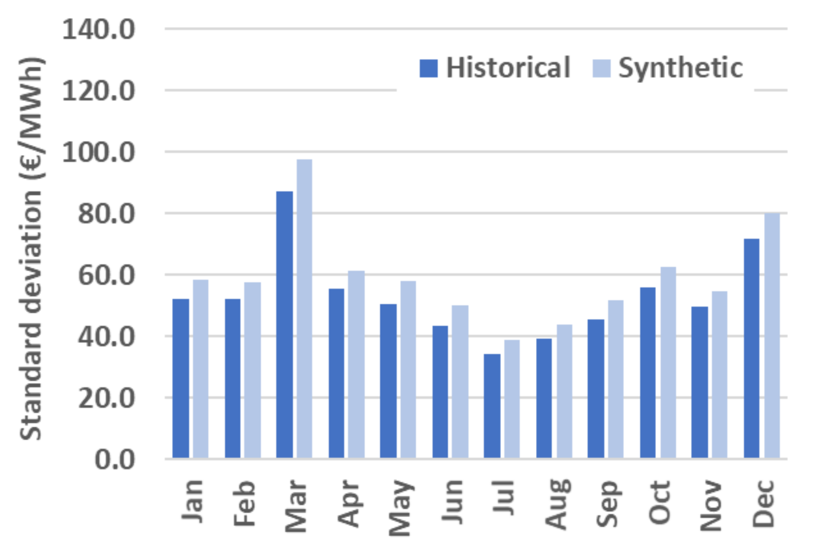
Reproduction of monthly-scale statistics

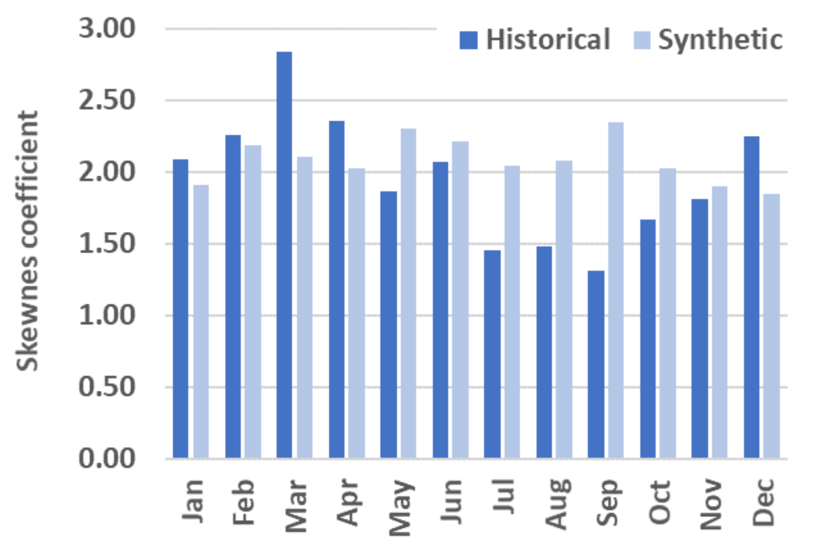






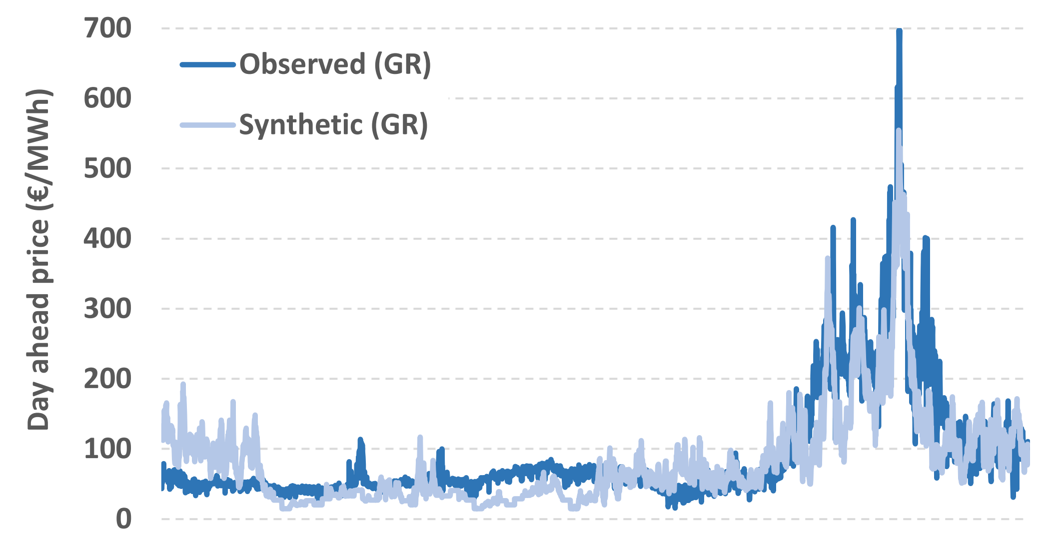


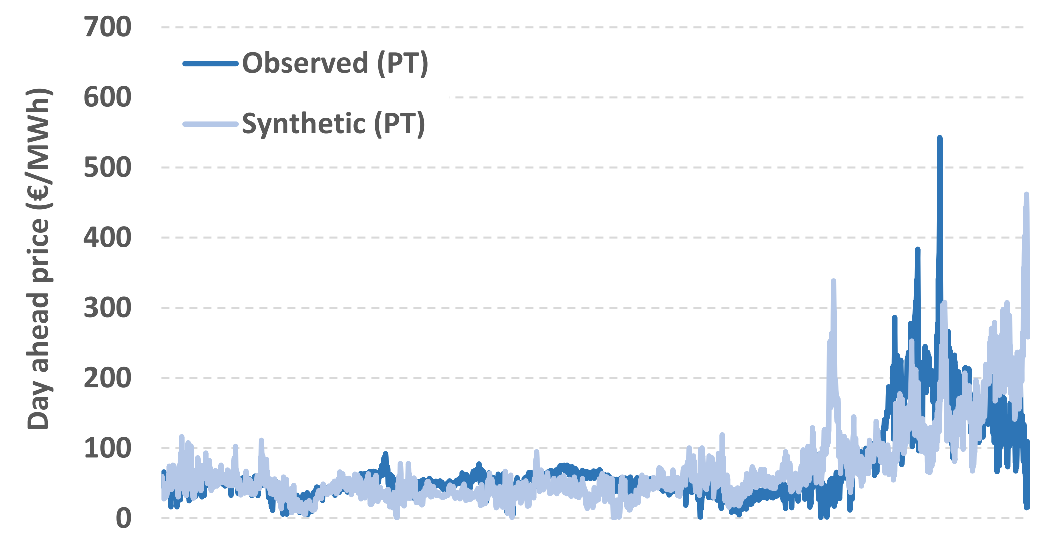




Can we trust on synthetic data for real-world decisions?

- The multiple peculiarities of electricity market price dynamics are satisfactory reproduced by **stationary stochastic models accounting for LTP**.
- The **short history of the current market structure**, which seems to be a major barrier in assigning "plausible" modeling assumptions and inferring parameters based on the observed data, is counterbalanced by the **broad experience on stochastics**, as a well-recognized and trustable approach for representing LTP-driven processes, also including the changing hydroclimate.
- Long synthetic prices reflecting a plethora of potential market conditions can be eventually used as **synthetic inputs** to energy system simulators, thus allowing to **quantify uncertainties** and evaluate their technical and financial performance in probabilistic means (e.g., risk).





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