Entropy, pricing and macroeconomics of pumped-storage systems

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Integrating hydropower with solar and wind related energies for sustainable future: Modelling, technology and management issues

Abstract

We propose a *pricing* scheme for the optimization of *macroeconomic* performance of pumped-storage systems, based on the statistical properties of both geophysical and economic processes. The argument consists in the need for identification of economic values concerning the *hub energy resource*; defined as the resource that comprises a reference energy currency for all involved *renewable energy sources (RES)* and discounts related *uncertainty*. In the case of pumped-storage systems the hub resource is the reservoir's water, as an energy benchmark for connected intermittent RESs. The uncertainty of related natural and economic processes is statistically quantifiable by *entropy*. It is the relation between the entropies of involved RESs that shapes total *energy value added*; thus the macroeconomic state of the integrated pumped-storage system. Consequently, there must be consideration not only on the entropy of wind, solar and precipitation patterns, but on the entropy of economic processes as well –such as demand preferences on either immediate energy use or *storage* for future availability. For pumped-storage macroeconomics, a price on the reservoir's *capacity scarcity* should also be imposed in order to shape a coherent pricing field with upper and lower bounds for the long-term stability of the pricing range and significant energy value added; which are the primary issues of generalized pumped-storage technology deployment.

Keywords: Entropy, pricing, macroeconomics, hub energy resource, RES, uncertainty, energy value added, energy storage, capacity scarcity

1. Entropy and hydro-economic adaptability

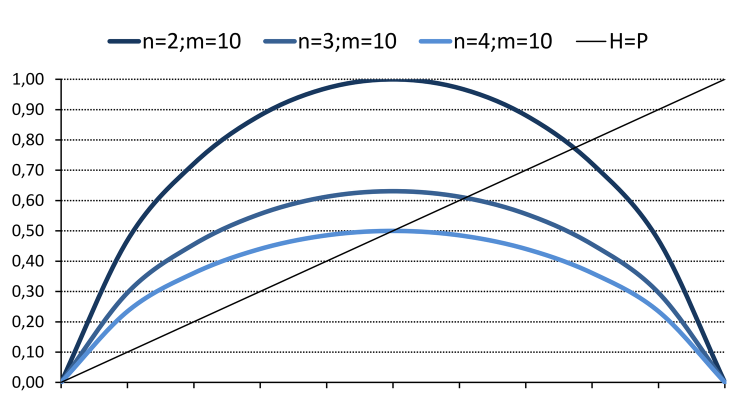
Shannon (1948) postulated a *statistical mechanical definition of entropy*, concerning the propagation complexity of a communication signal as a random variable *(X)* within a specific time-frame. We conceptualize processes of hydrological supply as signals that incorporate *uncertainty*; statistically quantified by entropy. Uncertainty may very well comprise a function of *structured complexity*. The connection of *entropy to water resource economics* lies in the effort of the economy to reconfigure its internal structure towards higher robustness against natural variability, via ***(a)*** charting an internal probability space of higher resolution (wider amplitude of technical capabilities to adequately meet a wider amplitude of natural events) and ***(b)*** and the use of an interpretation language of higher complexity (more options). Considering that for the *economic system* Shannon's formula *H(X)* comprises a function of its own language complexity as well, we may write:

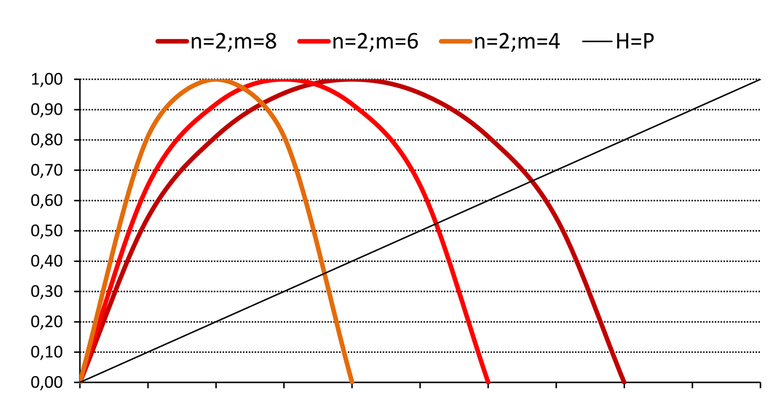
$$H(m;n) = -\sum_{i=1}^{m} P_i \cdot \log_n P_i \quad \text{s.t.} \sum_{i=1}^{m} P_i = 1$$

For a discrete-time random variable

$$H_X(x;n) = -\int f_X(x) \cdot \log_n\left(f_X(x)\right)dx \quad \text{s.t.} \int f_X(x)dx = 1$$

For a continuous-time random variable





The main difference of *H(m;n)* from the conventional conceptualization of *H(X)* is that it further comprises a function of the economic system's language complexity to interpret hydrological processes with a better encoding than the dual *(1,0)*. For pumped-storage deployment this is equivalent to more *alternative options (structures)* –thus reduction of dependence from natural uncertainty (Fig. 1). The sophistication of each of the structures affect the *entropy rate* (Fig. 2) as it makes them flexible towards a wider amplitude of events.

Entropy, the complexity language and the economic macrostate (macroeconomics)

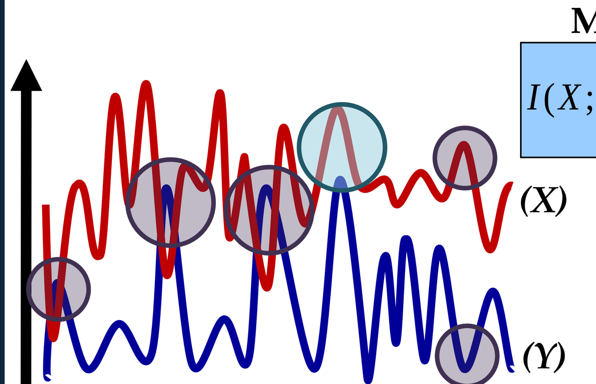
Primary efforts by economist Paul Samuelson (1960) –followed by Edward Jaynes (1991)- concerned the identification of how an economic system's *macrostate* may be shaped by its internal micro-structure (microeconomy). Following a more classical approach, Roegen (1971) argued that the utility of a resource is *reverse proportional to its entropy*, as high entropy signifies a higher cost (in terms of production factors' sacrifice) for its economic utilization.

3. Entropy of geophysical series and pumped-storage

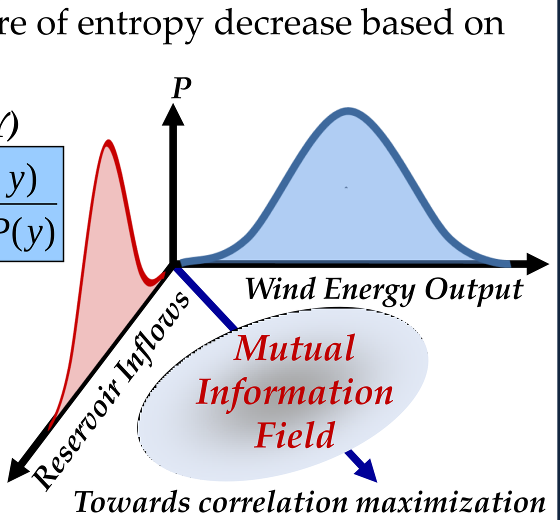
The optimization of a pumped-storage system primarily depends on its geophysical variables; the *natural inputs* of each connected *intermittent Renewable Energy Source (RES)*, as their coordination or independence will affect the pumped-storage cycle (i.e. a heavy rainfall event that fills the reservoir, with high wind energy output and low energy demand is probable to lead to lower utility of the system's main purpose due to failure to store wind energy excesses). *Mutual Information* is a scale-free measure of entropy decrease based on conditional probability of the two events' joint frequency.

Mutual Information *I(X;Y)*

$$I(X;Y) = \sum_{x \in X}\sum_{y \in Y} P(x,y)\log\frac{P(x,y)}{P(x)P(y)}$$

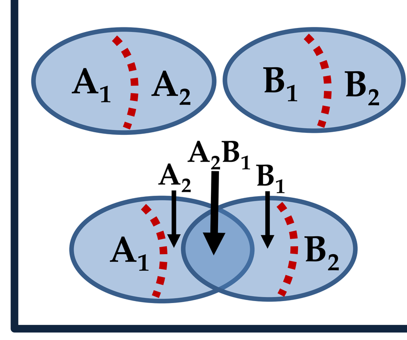


Time series (X) and (Y) share four (4) points of negative correlation (dark blue) and one (1) of positive (light blue)



3. Entropy and energy systems integration: Efficiency increase

Optimal integration consists in increasing the *statistical efficiency* (subsets A_1, B_1) of the system's components (sets A, B) by: ***(a)*** minimizing the *supply uncertainty* of connected intermittent sources (i.e. wind) and ***(b)*** minimizing *excessive output*, via storage to a *hub resource* (water in the reservoir).



Independent energy systems A+B
Efficiency: $(A_1+B_1)/(A+B)$
Losses: $(A_2+B_2)/(A+B)$, with $[A_1|B_2]=[B_1|A_2]=\varnothing$

Integrated energy systems A+B
Efficiency: $(A_1+B_1)/(A+B)$
Losses: $(A_2+B_2-A_2B_1)/(A+B)$

Efficiency increase due to system integration
$(A_2+B_2)/(A+B) > (A_2+B_2-A_2B_1)/(A+B)$

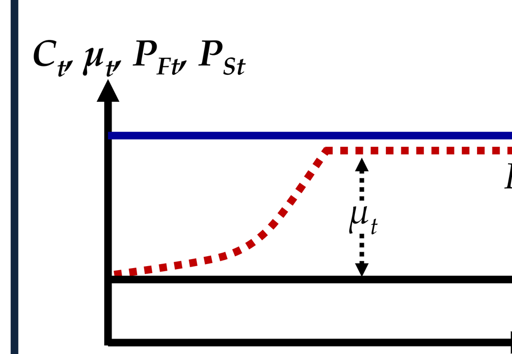
A wits problem for Hermes...

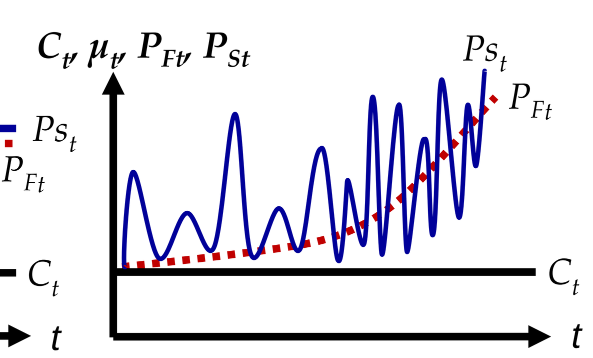
A master in economics and trade god asks himself: *How to put into cooperation **Aeolus** (symbolizing the god of winds) with **Achelous** (symbolizing the rivers as the most famous ancient Greek river-god) and tame their variability in order to conserve the Earth's energy resources for as long as possible?*

4. Entropy and energy systems pricing: The scarcity rent

The scarcity rent derives as a *shadow price* imposed on the depletion of a *biophysical surplus* and has a strong link to the *2nd Law of Thermodynamics* (Karakatsanis 2012). According to Roegen (1971), macroscopically, entropy manifests as *energy unavailability* for further production of thermo-mechanical work. The scarcity rent was primary developed for fossil fuels depletion in order to represent rising scarcity due to the *monotonic irreversibility* of fuel degradation to heat, as an imposed cost on future availability and need for a transition to new technologies (left figure) with price (P_{St}). The notion of scarcity rent can be well expanded to any kind of surplus, such as reservoir capacity and available water electricity output. Scarcity rents for renewable surpluses –such as water- represent only *immediate unavailability* (Karakatsanis et al. 2013); thus are fluctuating. For pumped-storage –with fluctuating water scarcity- the optimal pricing path is defined from the minimum price per unit time.

A: Fuel Reserve; C: Cost; P: Price; D: Demand; q: Extracted Quantity; μ: Scarcity Rent (Lagrange Multiplier); r: Discount Rate





Fuel depletion conditions

$$A_t = A_{t-1} - D_t$$
$$D_t / A_t > 0$$
$$dA/dt < 0$$

Scarcity Rent (SR)

$$\mu_{it} = P_{it} - C_{it}$$

Optimal Price Path

$$P_t = Min(P_F, P_S)_t$$

The derivation of scarcity rent from an optimization problem

The scarcity rent derives from the problem of optimizing a resource's pricing path, whether it is a fossil resource or a biophysical capacity (i.e. the free capacity of a reservoir or the available water from the minimum volume) as a *Net Present Value (NPV)* maximization under quantity constraints:

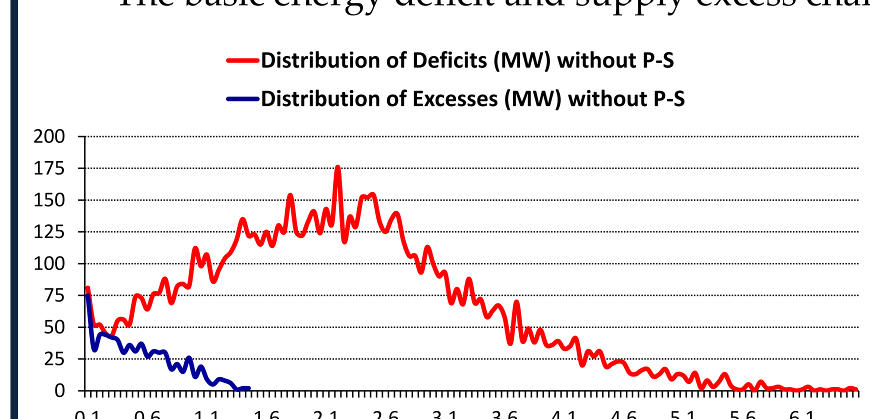
$$NPV = \sum_{t=0}^{T}\int_0^{q_t}\frac{(P_t(q) - C_t)dq}{(1+r)^t}$$

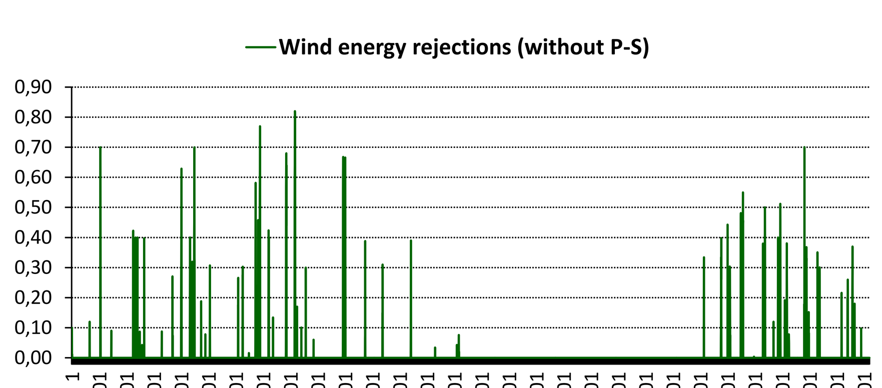
The Lagrange Multiplier μ is a dimensionless measure of constraint intensity on the economy across biophysical surplus depletion

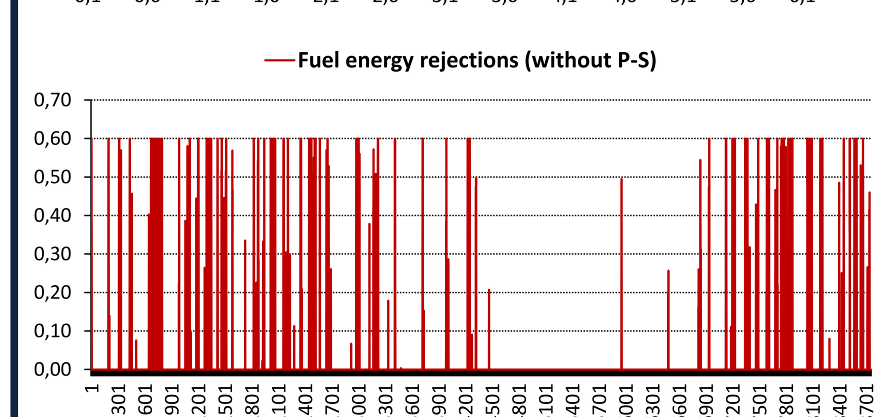
$$L = \sum_{t=0}^{T}\int_0^{q_t}\frac{(P_t(q) - C_t)dq}{(1+r)^t} + \mu \cdot \left(A_t - \sum_{t=0}^{T} q_t\right)$$

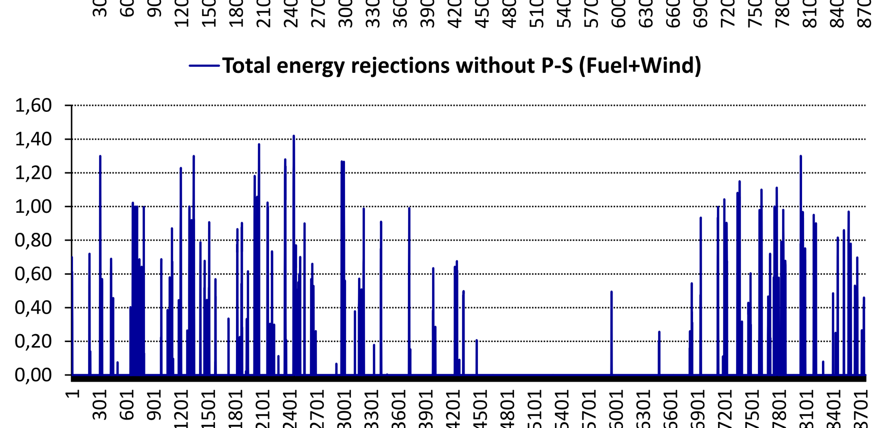
5. Simulation of a simple pumped-storage system

We model a simplified version of the Ikaria island pumped-storage system (Rippi 2013) that consists of: **(1)** a *diesel fuel* power station, **(2)** a *wind park* and **(3)** a *hydropower* station with an upper reservoir and a lower tank (by 400m) that gathers water after hydroelectricity output in order to store it for pumping. The basic energy deficit and supply excess characteristics of the system are presented below:



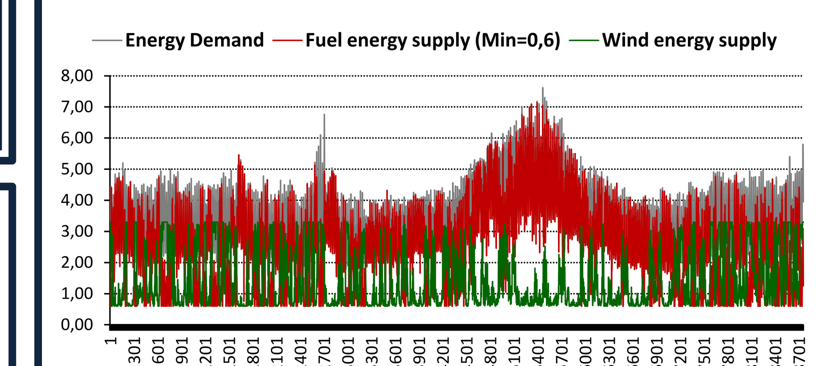


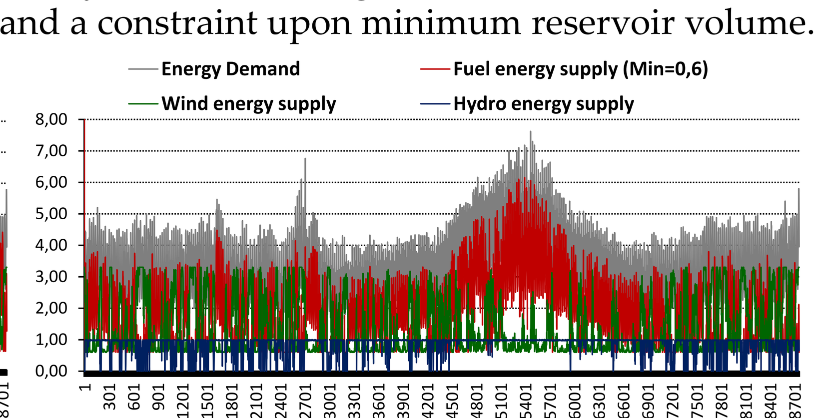


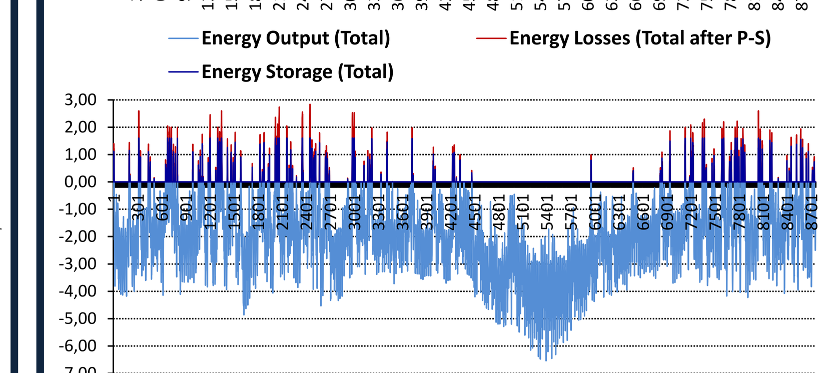


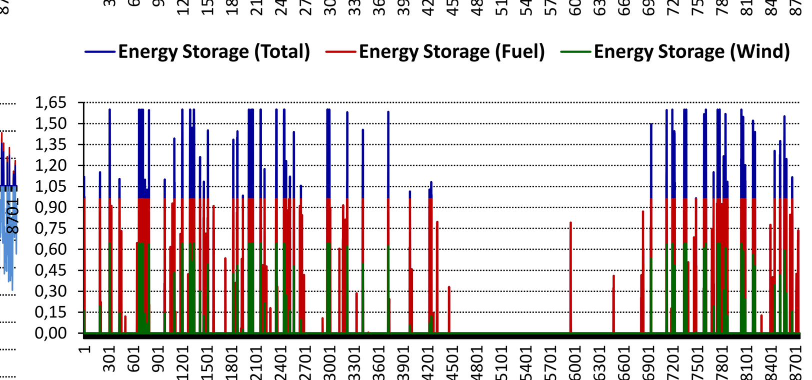
6. Pumped-storage for optimal energy resource composition

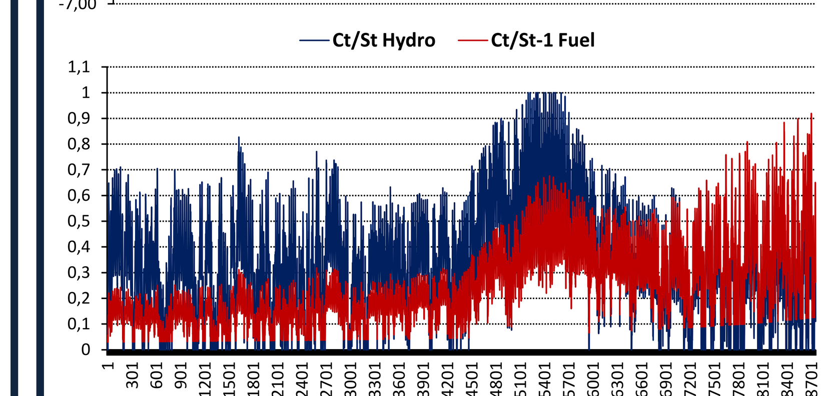
The energy strategy of the system consists in *satisfying electricity demand* by *minimizing the resource composition cost per unit time* -including the depletion cost for each resource (*Scarcity Rent*, *SR=μ*). P-S hydropower is introduced to an initial mix of fuel and wind (upper figures). The system achieves 77,92% storage of total previous excesses; 80% of fuel output excesses –that contributed by 80,92% to total excesses- and 69,1% of wind –that contributed by 19,08% to total excesses (middle figures). Resource use optimization occurs for minimum *depletion ratio* per unit time (C_{it}/S_{it}, as the basis of the scarcity rent concept) for each resource. P-S hydropower reduces the fuel depletion ratio by 48,9% (lower figures) –with fuel exhaustion assumed at cumulative output of 20MW and a constraint upon minimum reservoir volume.

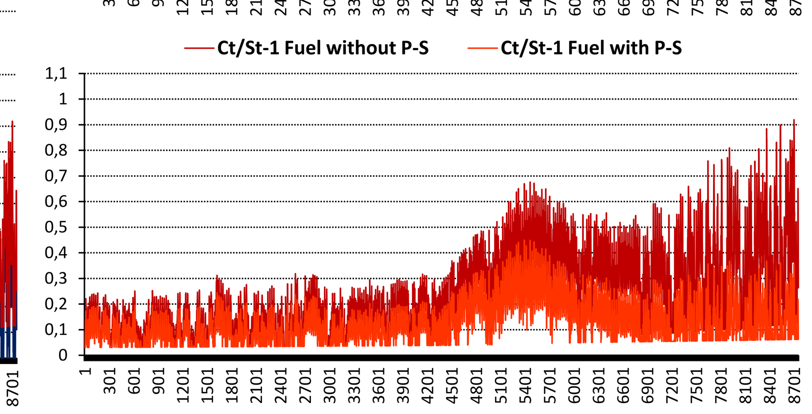












Non-stationarity of the Depletion Ratio (and Scarcity Rent)

A rising trend of the fuel depletion ratio (lower right diagram) is obvious in both cases; however its evolution is more unstable in the first case. The depletion ratio C_t/A_{t-1} is constantly pressured towards a monotonic increase due to the minimum depletion of the fuel reserve -equal to the quantity needed to produce 0,6MW/h. Observed drops -due to high substitution from wind and hydropower- are only temporary as the ratio is increasingly more sensitive towards A_{t-1} and unpredictable around a rising trend. The utility of renewables consists in the delay of this process. Although renewable, hydropower is affected by depleting fuel reserves, as the economy resorts more frequently to it; being increasingly depended on hydrological uncertainty (entropy) related to reservoir recharge.

7. Conclusions

- ✓ Pumped-storage is equivalent to an increase of the economic system's complexity language towards a more sophisticated management of intermittent energy inputs.
- ✓ Maximization of intermittent renewables' penetration and conservation of fuel reserves for future availability can lead to an optimal use path of non-renewable resources.
- ✓ Minimization of the scarcity rent may comprise a macroeconomic pricing target that is also in accordance to the 2nd Law (via the imposing of shadow prices across fuel depletion).

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