Entropy, pricing and productivity of pumped-storage

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European Geosciences Union (EGU)

General Assembly 2016

Active Planet

Session ERE 3.8 / HS 5.7

Renewable energy and environmental systems: modelling, control and management for a sustainable future

Project Description

Pumped-storage constitutes today a mature method of bulk electricity storage in the form of hydropower. This bulk electricity *storability* upgrades the *economic value* of hydropower as it may mitigate –or even neutralize- *stochastic* effects deriving from various geophysical and socioeconomic factors, which produce numerous load balance inefficiencies due to increased *uncertainty*. Pumped-storage further holds a key role for unifying intermittent renewable (i.e. wind, solar) units with controllable non-renewable (i.e. nuclear, coal) fuel electricity generation plants into integrated *energy systems*. We develop a set of indicators for the measurement of performance of pumped-storage, in terms of the latter's energy and financial contribution to the energy system. More specifically, we use the concept of *entropy* in order to examine: **(1)** the statistical features -and correlations- of the energy system's intermittent components and **(2)** the statistical features of electricity demand prediction deviations. In this way, the macroeconomics of pumped-storage emerge naturally from its statistical features (Karakatsanis et al. 2014). In addition, these findings are combined to actual daily loads. Hence, not only the amount of energy harvested from the pumped-storage component is expected to be important, but the harvesting time as well, as the *intraday price* of electricity varies significantly. Additionally, the structure of the pumped-storage market proves to be a significant factor as well for the system's energy and financial performance (Paine et al. 2014). According to the above, we aim at postulating a set of general rules on the *productivity* of pumped-storage for (integrated) energy systems.

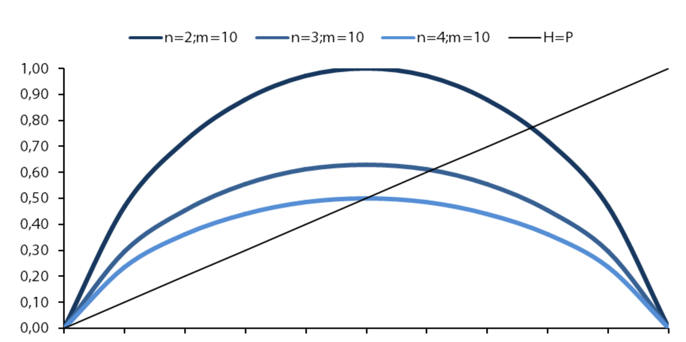
Keywords: pumped-storage, storability, economic value of hydropower, stochastic effects, uncertainty, energy systems, entropy, intraday electricity price, productivity

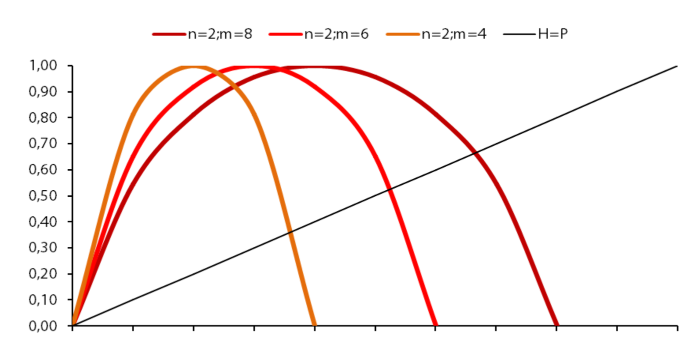
Contribution of the project

The main obstacle for integrating ***intermittent*** renewables with base load sources into a reliable, unified ***hybrid energy system*** are the elements that lack variability buffering ability. As from this uncontrolled uncertainty derive many operational constraints for continuous load balancing, ***pumped-storage*** is able to mitigate them, both for continental and remote grids. An additional challenge is to achieve continuous balancing via a ***market system***. The conditions under which load imbalances can be reduced -and managed- to hydroelectric potential are examined, so that a future pumped-storage market can operate as a ***critical subsystem*** of the Greek national grid.

1. Entropy and the pumped-storage operation

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. Generalizing Shannon entropy as *H(X;n)* –considering that it comprises a function of the used language's sophistication as well (defined by the logarithm base)- we may write:





$$H(m;n) = -\sum_{i=1}^{m} P_i \cdot log_n P_i$$

$$H_X(x;n) = -\int f_X(x)\cdot \log_n (f_X(x))dx$$

For a discrete-time random variable | s.t. $\Sigma P_i=1$ and $\int f_X(x)dx=1$ | **For a continuous-time random variable**

The Entropy of a process (i.e. time-series) comprises either a function of pure randomness or *structured complexity*; which signifies a *wider range* of probabilities per unit time (variability). The connection of *entropy to water resource economics* lies in the effort to identify the economy's *exposure to hydrological variability* as well as how it can *reconfigure its internal structure* –via pumped-storage- in order to decouple itself from it.

Statistical manifestations of entropy in pumped-storage economics

- Statistically, entropy is manifested as *uncertainty* (weak form) or *structural complexity* (strong form; concerns even structural uncertainty) of water supply probability.
- Statistically, *entropy buffering* is equivalent to a *structural change*; a shift of the economy's demand for natural water supply towards lower distribution parameters $\{E[X], \sigma^2, \sigma\}$.
- Statistically, the utility of an energy source (i.e. wind) is *reverse proportional to its entropy*, as high entropy of natural supply signifies economic structural exposure to higher probability of supply failure due to a wider range of probable geophysical events.

2. Entropy and the pumped-storage market

Which is the fundamental economic attribute of electricity?

Electricity must be delivered on demand and cannot be stored spontaneously. Hence, demand and supply ideally must constantly (24/7) coincide.

What reasons prevent the use of only one type of energy technology?

Technical limitations, such as minimum generation per unit time and minimum response time for load generation change (applies for lignite-fired plants).

How often is electricity demand perfectly predicted so that supply meets it?

Almost never, in any energy system of the planet → Deviations between demand and supply → Energy system inefficiencies → Deficit/surplus management.

Which main economic service is encapsulated in pumped-storage systems?

It improves the overall performance of the energy system via the reduction of incorporated uncertainty (entropy). Specifically:

- ✓ Stabilizing load variability from intermittent renewables (i.e. solar, wind)
- ✓ Utilizing stored intermittent energy deterministically at desirable future time
- ✓ Offsetting the deviations of power demand predictions

Independent energy systems A+B

Efficiency: $(A_1+B_1)/(A+B)$

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

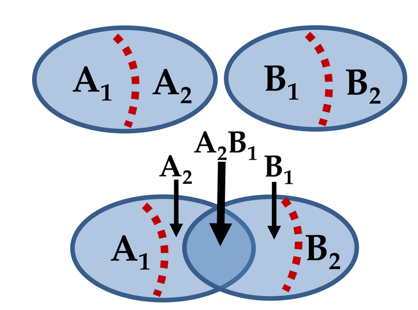
Integrated energy systems A+B

Efficiency: $(A_1+B_1)/(A+B)$

Losses: $(A_2+B_2-A_2B_1)/(A+B)$

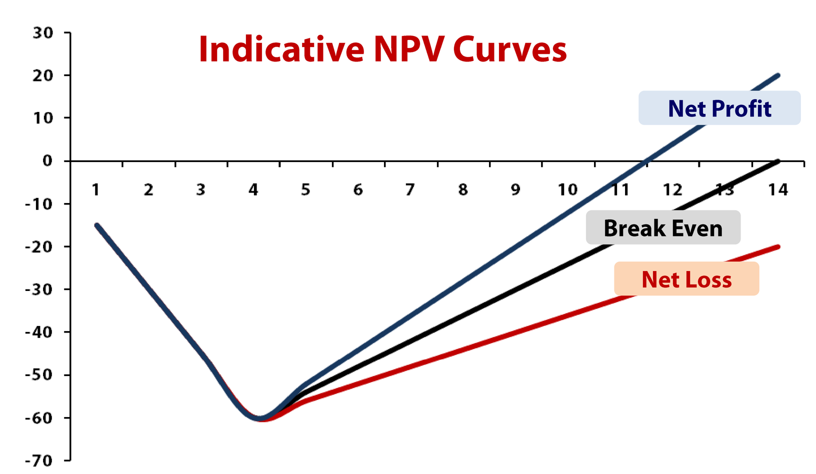
Efficiency increase due to system integration

$(A_2+B_2)/(A+B) > (A_2+B_2-A_2B_1)/(A+B)$



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).

3. Entropy and the pricing of hydropower capital



Net Present Value (NPV) = The discounted (by the *Minimum Risk* alternative investment → the *Bank Discount Rate*) net profit that the pumped-storage system produces across its total life (Is it more profitable to deposit my money in the bank or invest it in the pumped-storage hydropower project?):

$$NPV = -\sum_{t=0}^{T_I} K_t + \sum_{t=T_I+1}^{T_K} \frac{B_t - C_t}{(1+r)^t}$$

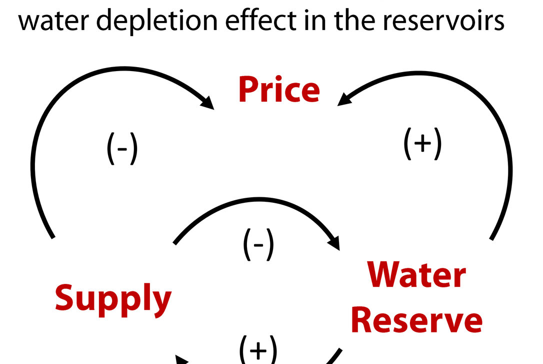
K = Initial Investment Costs (Non Operational)

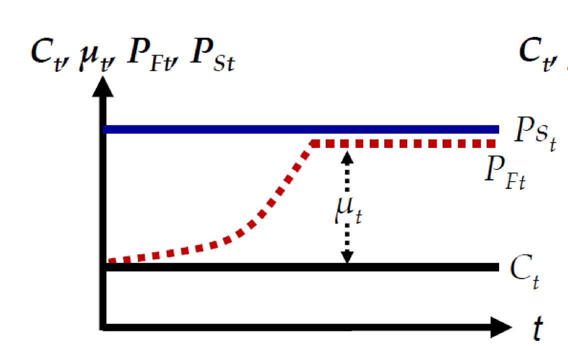
$\mathbf{B_t}$ = Revenue in every time t (Operational)

$\mathbf{C_t}$ = Cost in every time t (Operational)

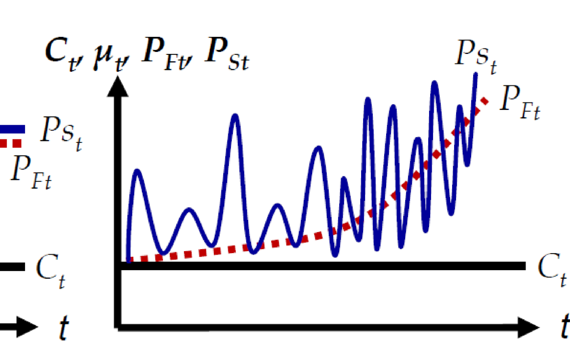
r = Minimum Risk Investment (Bank Discount Rate)

A pricing system based on the *Hotelling's Rule* stabilizes the price as it incorporates the water depletion effect in the reservoirs





The *total fuel price* consists of the sum of the *cost* (C_t) and *scarcity rent* (μ_t), until it meets the price of the *alternative source* (P_s)



The price of hydropower as *alternative energy source* is variable along with its hydrological inputs

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

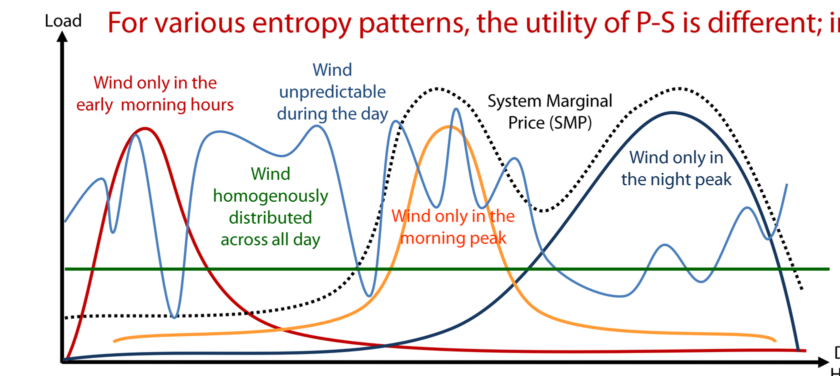
$$\mu_{it} = P_{it} - C_{it}$$

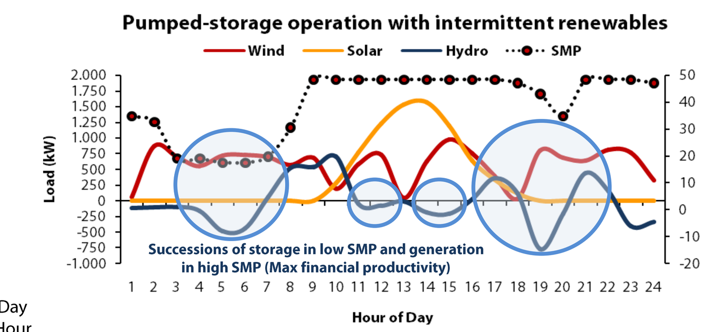
$$P_t = Min(P_F, P_S)_t$$

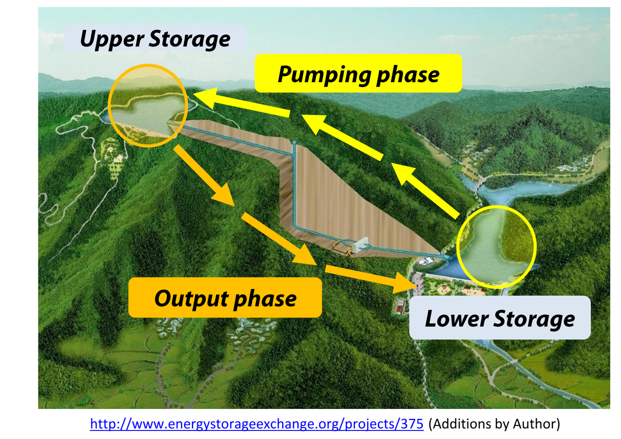
The NPV maximization must be adjusted to take into account the constraint upon the availability of the water resource that is used for hydropower generation. The Lagrange Multiplier **μ** is a dimensionless measure of *constraint intensity* on the *physical availability of water across its use for hydropower output*; equal to the difference between the price and the cost. For generation or pumping, hydropower is chosen until –by its price $\mathbf{P_F}$- becomes more expensive choice than the *substitute resource's price* $\mathbf{P_S}$.

4. Entropy, intermittency patterns and P-S productivity

For various entropy patterns, the utility of P-S is different; increasing proportionally with the uncertainty of wind.





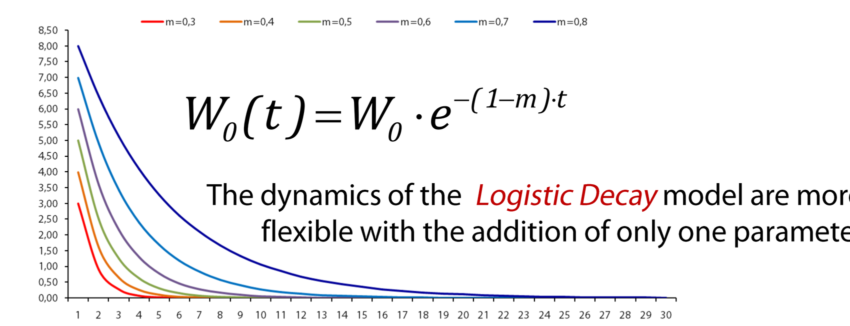


Entropy and the utility of pumped-storage

The *statistical features* of intra-day prices and intermittent units (eg. *succession/coincidence* with demand) determine pumped-storage utility.

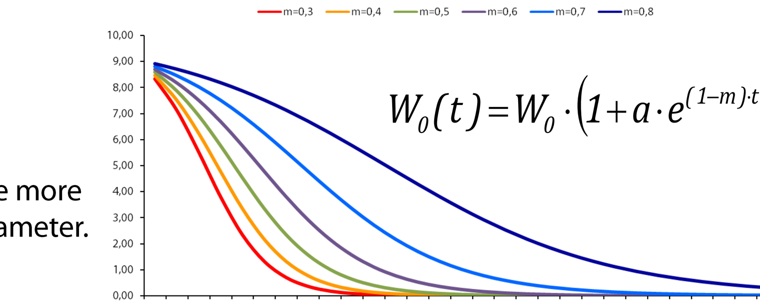
Recycling hydropower capital

Hydropower capital recycling, extends the time that an initial amount of pumped water W_0 resides in the economic system to produce economic value- under constant outflow from the reservoir– defined as *economic residence time of water*. Assuming a constant efficiency rate *m*, we can model residence times with two (2) models: ***(a)*** *Exponential* and ***(b)*** the *Logistic* model (with *a>0*, as a parameter of proximity to W_0. Here, *a=0,1*).



$$W_0(t) = W_0 \cdot e^{-(1-m)\cdot t}$$

The dynamics of the *Logistic Decay* model are more flexible with the addition of only one parameter.

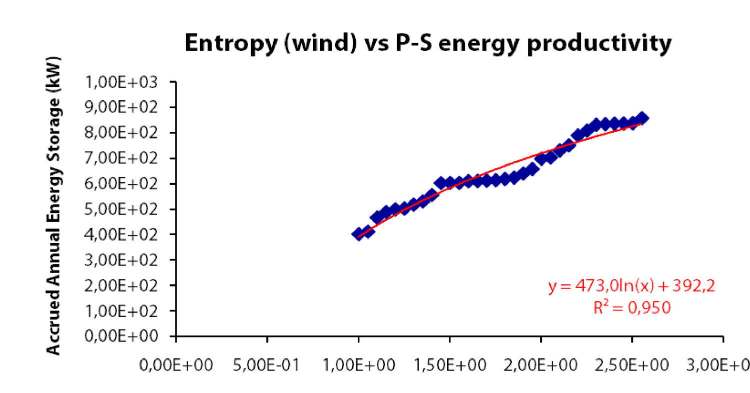


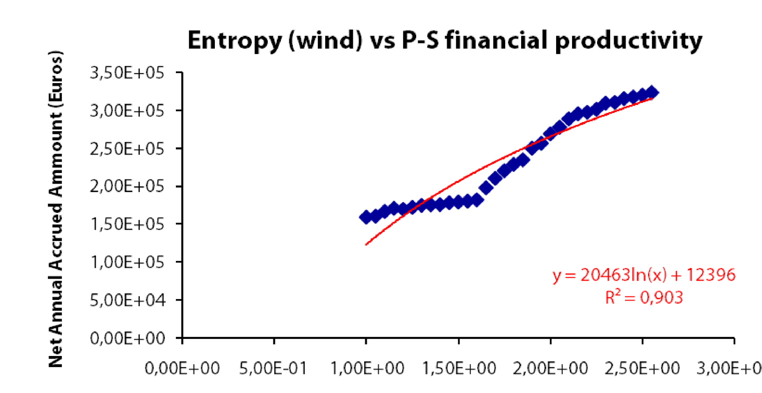
$$W_0(t) = W_0 \cdot \left(1 + a\cdot e^{(1-m)\cdot t}\right)^{-1}$$

5. Simulation of a synthetic pumped-storage system

The relation between **(a)** the Entropy of wind load distribution (according to the 2-parameter Weibull distribution and its derived entropy), **(b)** System Marginal Price (SMP), **(c)** Accrued Energy Storage and **(d)** Net Accrued Financial Gain is examined based on the following function:

$$U_{PS} = f\left(Correl(H_{LOAD-W}; SMP)\right)$$





6. Conclusions

- ✓ Pumped-storage is *equivalent* to an increase of the economic system's *complexity language* towards a more sophisticated management of intermittent energy inputs.
- ✓ Pumped-storage upgrades the energy system's flexibility and operates optimally in *market context*, in which the pricing criteria determine its energy and financial performance.
- ✓ Across the unification of energy systems with specific technical and pricing criteria, the *entropy of the intermittent elements* determines the utility of pumped-storage units.
- ✓ The *energy and financial productivity of pumped-storage* –with water scarcity pricing- in simple/remote power systems is *proportional to the entropy of intermittent elements.*
- ✓ Intermittent renewables' penetration with pumped-storage can lead *under specific technical and pricing conditions* to an optimal use path of non-renewable resources.

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Acknowledgments

This research has been financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program ***Education and Lifelong Learning*** of the National Strategic Reference Framework (NSRF) – Research Funding Program: ARISTEIA II: Reinforcement of the interdisciplinary and/or inter-institutional research and innovation.