Energy-Water Nexus: An Input-Output Dynamical MODEL

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General

To establish a rational for better energy-water nexus management.

Specifics

- Make a broad review in order to frame the issues;
- Propose a model that could be adapted for local solutions (Regional Economy — Supply Chain Model).

Energy-Water Issues (1)

Highlights(1)

- There are tradeoffs: To generate energy, massive quantities of water are consumed, and to deliver clean water, massive quantities of energy are consumed;
- Both are essential to our health, quality of life, and economic growth, and demand for these resources continues to rise;
- People die, and one cannot grow food, if water is not available. Without energy, one cannot run computers, or power homes, schools, offices, farms, and industrial plants.
- As the world's population grows in number and affluence, the demands for both resources are increasing faster than ever.

Energy-Water Issues(2)

Highlights(2)

- Only about 2.5% of the world's water is freshwater. Unfortunately, less than 1% is accessible via surface sources and aquifers, and the rest is imprisoned in underground reservoirs and in permanent ice and snow cover; Also, the available water is often not clean or not located close to population centers.
- Desalination, a process that removes salt from water, is the most energy-intensive and expensive option for treating water and is used where alternatives are very limited;
- Many people are concerned about the perils of peak oil —— running out of cheap oil, and only a few are voicing concerns about peak water. Almost no one is addressing the conflict between the two: water restrictions are hampering solutions for generating more energy, and energy problems, particularly rising prices, are curtailing efforts to supply more clean water;

Energy-Water Nexus (1)

Central Problem: Water Restrictions

- Water is ubiquitous in energy production: in power generation; the extraction, transport and processing of fossil fuels; and, increasingly, in irrigation for the cultivation of raw materials used for the production of biofuels. Similarly, energy is vital to the water supply needed to power that collect, transport, distribution and treat it systems;
- Each faces increasing demands and restrictions in many areas as a result of economic and population growth and climate change, which amplify the mutual vulnerability of energy and water;
- Globally, agriculture is the main user of water, accounting for 70% of water use, followed by industry (including mining and power generation) in 19% and municipal networks that meet the water needs of public and private users in 11%.

Energy-Water Nexus (2)

The Water and Energy Standoff Solutions

- The choices on the future mix of plants used to generate electricity can relieve tension between water and energy. Renewable energy technologies such as wind turbines and photovoltaic panels use little or no water;
- Even fossil fuel technologies provide opportunities to reduce water demand;
- New refrigeration technologies, such as cooling systems and hybrid dry, can also reduce pressure on water systems;
- If energy companies have difficulty finding enough water to cool it´s power plants, blackouts can force them to buy electricity from other sources, which can raise utility bills.

Energy-Water Nexus (3)

The Art of Mathematical Modeling

- This theme has attracted world-wide attention in various contexts like economy, ecology, environment, energy policies and to small, medium and large industries;
- The subject emerges many distortions of information, conflict of interest and undue desire and even contributions from many to the problem detected does not proceed properly there;
- One way to consolidate opinion and strengthen the arguments is through the effort of mathematical modeling of these contexts;

Energy-Water Nexus (4)

The Art of Mathematical Modeling

- Optimal Solution requires Mathematical Modeling;
- The mathematical tool has the power to, in a few lines of information; clarify irrefutable arguments, as a basis for informed decisions to be made.
- Energy-Water Nexus is a real problem that requires complex solution. It is necessary to analyze in the general context (Macro-Solution Optimization), that will serve to long term planning (05–10 years) and supply chain context (Local-Solution Optimization),that will serve to short term planning (01–05 years);
- This work proposes a mathematical supply chain model to analyze the Energy-Water Nexus Issue: An Input-Output Dynamical Model.

Energy-Water Nexus: An Input-Output Dynamical Model

E-W Nexus: An Input-Output Dynamical Model (1)

The Supply Chain Model

- The supply chain management is a central tool in business administration. The input-output matrix, which is part of an underlying mathematical model, summarizes the matching of supply and demand amongst the various sectors of the economy;
- Two important economic variables are supply, s, and demand, d. It is assumed that if demand grows, then supply will grow, or should grow, to match it;
- Since demand is always varying, there will be always a dynamic equilibrium. The system is, in general, always moving. It is the dynamics of this movement that one wants to study and control,and in the case of the energy-water interplay this is crucial, since these two variables are closely intertwined.

E-W Nexus: An Input-Output Dynamical Model (2)

Input-Output Dynamics

The equilibrium point is defined by:

$$\boldsymbol{s}(t) = \boldsymbol{d}(t). \tag{1}$$

The dynamical systems works:

$$\begin{aligned} \frac{dx}{dt} &= u \\ x &= Ax + B\frac{dx}{dt} + s \\ u &= K(d - s) \end{aligned} \tag{2}$$

- $\boldsymbol{x}$ is the system total production;
- $\boldsymbol{Ax}$ is part of the total production which is used in the production process;
- $\boldsymbol{B}\frac{d\boldsymbol{x}}{dt}$ is the part of the total production which is put in stock (energy and water need to be stocked);
- $\boldsymbol{s}$ is the supply to satisfy the external demand.

E-W Nexus: An Input-Output Dynamical Model

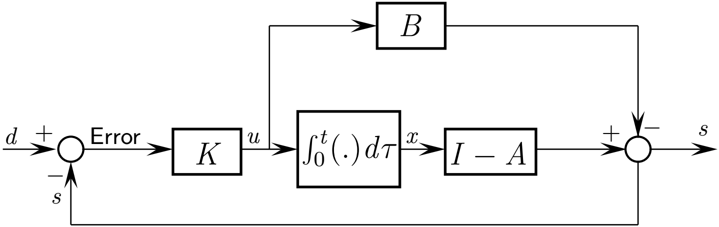

Figura: Block diagram of a supply chain dynamical model.

$$\frac{dx}{dt} = u$$
$$x = Ax + B\frac{dx}{dt} + s \qquad (3)$$
$$u = K(d - s)$$

- if $\boldsymbol{x}$ is a straight, $\boldsymbol{B}\frac{d\boldsymbol{x}}{dt}$ is constant;
- if $\boldsymbol{x}$ is constant, $\boldsymbol{B}\frac{d\boldsymbol{x}}{dt}$ is zero;
- ...

$$\frac{dx}{dt} = -K(I - BK)^{-1}(I - A)x + K(I - BK)^{-1}d \qquad (4)$$
$$s = (I - BK)^{-1}(I - A)x - (I - BK)^{-1}BKd \qquad (5)$$

E-W Nexus: An Input-Output Dynamical Model

Simulations

The following values were used:

$$\boldsymbol{A} = \begin{bmatrix} 0.30 & 0.15 \\ 0.10 & 0.13 \end{bmatrix}; \quad \boldsymbol{B} = \begin{bmatrix} 0.020 & 0.010 \\ 0.010 & 0.025 \end{bmatrix}; \quad \boldsymbol{K} = \begin{bmatrix} 0.30 & k_{12} \\ k_{21} & 1.25 \end{bmatrix}$$

- Stability Condition — The matrix $-K(I - BK)^{-1}(I - A)$ characteristics polynomial roots should have negative real parts;
- The $\boldsymbol{B}$ Matrix — The problem with reducing the storage policy is the risk of go through periods of abrupt change in demand and the company be required to set up a matrix K with high values, destabilizing the productive system. In case of availability of energy, for example, the elimination of stocks of energy can cause an economic collapse.

Simulations

- The $\boldsymbol{K}$ Matrix — As already mentioned, it is responsible for the production planning. It was named control force;
- The Objective Functional — The model described leads the analysis of input-output matrix in the direction of modeling a system of optimal control.The quadratic sum of the error (difference between demand and supply) was used as a functional objective, but any other criterion could be used (including cost, for instance).

Separated Policies for Energy and Water

By changing the values of k_{11} and k_{22}, one could diminish the errors. This would have the effect of increasing the intensity of the control effort (cost). The eigenvalues of matrix $-K(I-BK)^{-1}(I-A)$ are:

$$K = \begin{bmatrix} 0.30 & 0.00 \\ 0.00 & 1.25 \end{bmatrix} \quad \rightarrow \quad \begin{cases} \lambda_1 = -1.13 \\ \lambda_2 = -0.21 \end{cases}$$

The error can be seen from trajectories shown in the graphics in figures 2 and 3. The sum of squared errors was 316.

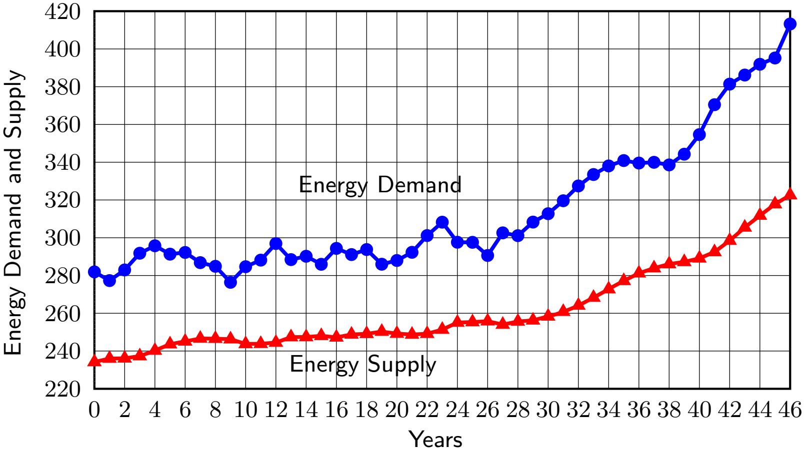

Figura: Energy demand and supply curves, when the K matrix off-diagonal elements are null, i.e., $k_{12} = 0$ and $k_{21} = 0$ (independent control of energy and water).

E-W Nexus: An Input-Output Dynamical Model

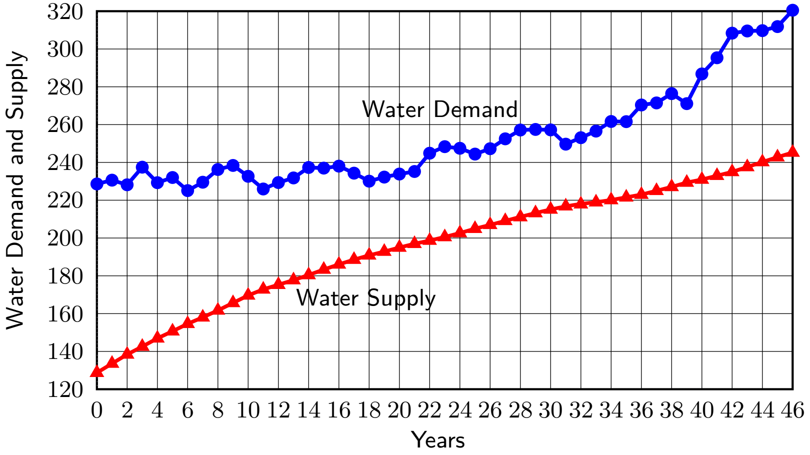

Figura: Water demand and supply curves, when the K matrix off-diagonal elements are null, i.e., $k_{12} = 0$ and $k_{21} = 0$ (independent control of energy and water).

E-W Nexus: An Input-Output Dynamical Model

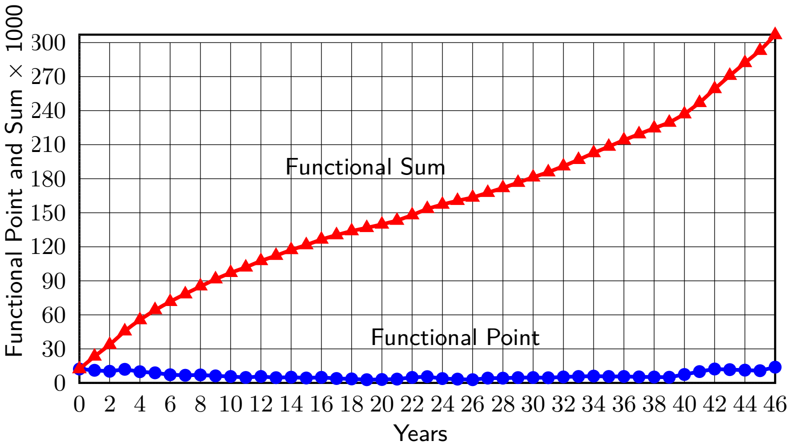

Figura: Functional curves, when the K matrix off-diagonal elements are null (independent control of energy and water).

Integrated Policies for Energy and Water

Instead of increasing the intensity of the separable controls (k_{11} and k_{12}), one introduces non-zero elements in the off-diagonal of the matrix K, namely, $k_{12} \neq 0$ and $k_{21} \neq 0$. The eigenvalues of matrix $-K(I - BK)^{-1}(I - A)$ are:

$$K = \begin{bmatrix} 0.30 & 0.50 \\ -0.80 & 1.25 \end{bmatrix} \quad \rightarrow \quad \begin{cases} \lambda_1 = -0.75 \\ \lambda_2 = -0.63 \end{cases}$$

The error can be seen from trajectories shown in the graphics in figures 5 and 6. It is visible that the error, in this case, is smaller than in the case of separated policies. The sum of squared errors was 126. The ratio was then 2.50.

The results presented here depended, of course, upon the matrices A and B that were used. The objective of the simulation is to highlight the flexibility that one can achieve.

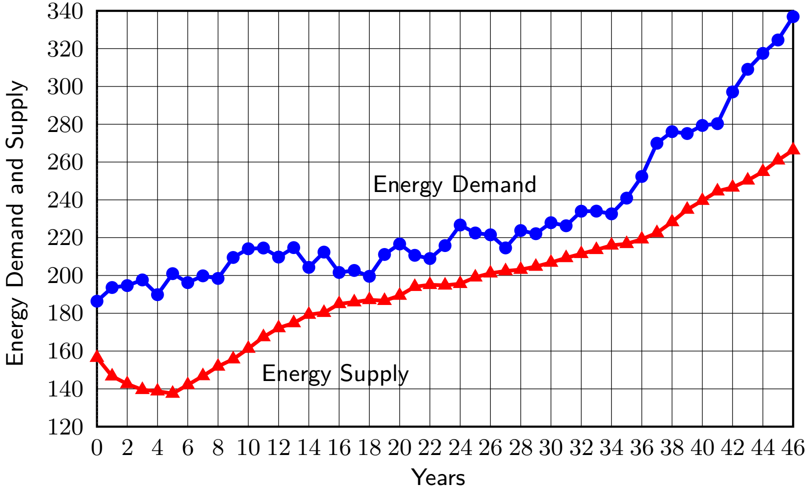

Figura: Energy demand and supply curves, when the K matrix off-diagonal elements are non-null, with values $k_{12} = 0.50$ and $k_{21} = -080$ (integrated control of energy and water).

E-W Nexus: An Input-Output Dynamical Model

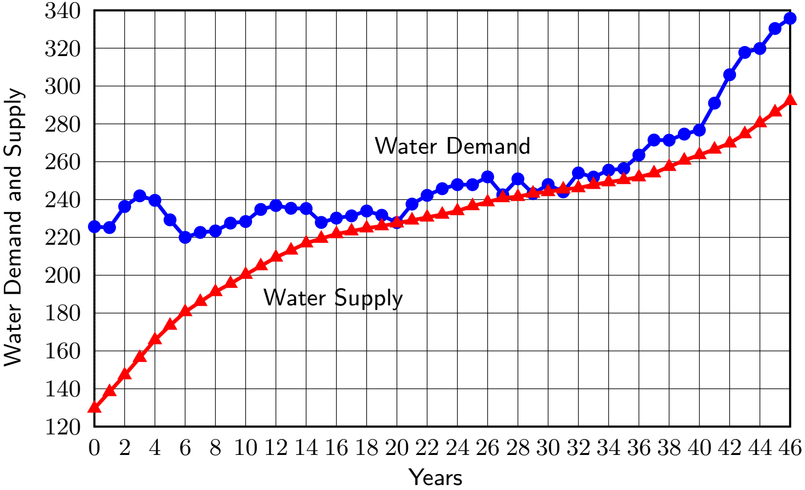

Figura: Water demand and supply curves, when the K matrix off-diagonal elements are non-null, with values $k_{12} = 0.50$ and $k_{21} = -080$ (integrated control of energy and water).

E-W Nexus: An Input-Output Dynamical Model

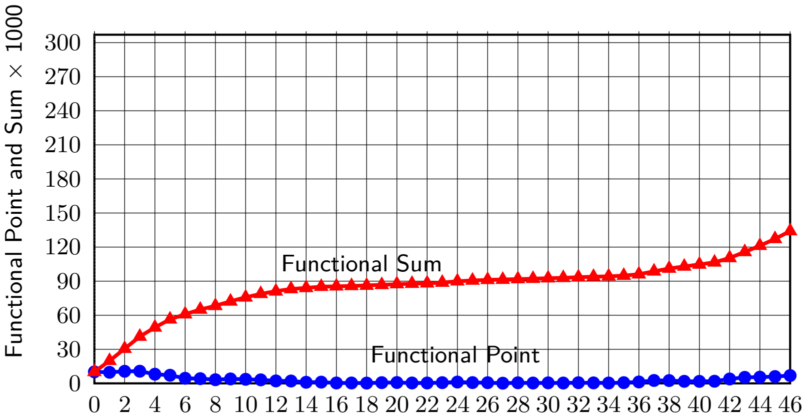

Figura: Functional curves, when the K matrix off-diagonal elements are not null (integrated control of energy and water).

Three Time Scales for Control

There are three time scales for control. The manager will act in the elements of matrix:

- A (technology development)
- B (stock policy), and
- K (production planning).

In the simulations presented here, the optimality criterion was the quadratic error (to be minimized), and the A and B matrix were fixed. Only the elements of matrix K were used as parametric controls.
A more general objective functional can be used, including, for instance, the control cost.
One can use probabilistic algorithms in order to compute the parametric controls.

Energy-Water Nexus: Conclusions (1)

- The time has come to consider both issues as one.
- As the population grows, water will be more and more scarce. And it cannot be substituted. It will be harder and harder to make water, a precious liquid, available to the population and its economy. More and more energy will be needed. The case of sea water desalination is emblematic; reverse osmosis requires lots of energy. Energy, for its turn, will need more and more water in order to be produced. The only way to escape from this trap is to improve the technology for producing energy (fuels, thermoelectric, for instance) using less water, on one hand, and use progressively more energy primary sources that do not need water in order to produce usable energy, on the other hand.

Energy-Water Nexus: Conclusions (2)

- There is a close connection, or nexus, between energy and water. It takes a significant amount of water to create energy. Water is used to cool steam electric power plants — fueled by coal, oil, natural gas and nuclear power — and is required to generate hydropower. Water is also used in great quantities during fuel extraction, refining and production. It takes a significant amount of energy to extract, move and treat water for drinking and irrigation. It is used in the collection, treatment and disposal of waste water. Energy is also consumed when water is used by households and industry, especially through heating and cooling. Water and energy policy, planning and management must be integrated to encourage conservation, motivate innovation and ensure sustainable use of water and energy.
- One may not realize it, but when one uses energy, one is also using water indirectly — lots of it!

Energy-Water Nexus: Suggestions For Future Studies(2)

A National Energy-Water Supply Chain Model

In the case of two or more country´s regions, it´s possible to make the local matrixes intertwined. One can insert more variables in the problem. This will increase the quantity of matrixes elements . . .

With the local matrixes intertwined, the authorities could minimize the costs and risk of non energy-water availability.

Energy-Water Nexus: Questions???

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