Energy and the capital of nations

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Energy and environmental system interactions: Modelling and policy

Project Description

The economically useful time of *fossil fuels* in Earth is estimated in just ~160 years, while humanity itself counts ~150·10³ years. Within only ~0,15% of this time, humanity has used more energy, accumulating so much wealth than within the rest of its existence time. According to this perspective, the availability of heat gradients is what fundamentally drives the evolution of *economic systems*, via the extensive enhancement –or even substitution- of human labor (Ayres and Warr 2009). In the modern *industrial civilization* it is estimated (Kümmel 2011) that the average human ability to generate wealth (productivity) has increased by ~40%-50% –including the effects from the growth of human population- further augmented by significant economies of scale achieved in the industrial era. This process led to significant accumulation of surpluses that generally have the form of *capital*. Although capital is frequently confused with the stock of mechanical equipment, capital can be generalized as any form of accumulated (not currently consumed) *production factor* that can deliver a benefit in the future. In that sense, capital is found in various forms, such as machinery, technology or natural resources and environmental capacities. While it is expected that anthropogenic forms of capital are accumulated along the increase of energy use, *natural capital* should be declining, due to the validity of the *Second Law of Thermodynamics* (2nd Law), *entropy* production and –in turn- the *irreversible* (monotonic) consumption of *exergy* (Wall 2005). Regressions of the *LINear EXponential* (LINEX) function (an economic growth function depending *linearly* on energy and *exponentially* on *output elasticity* quotients) (Lindenbeger and Kummel 2011) for a number of industrialized economies - like the USA, Germany and Japan, found that output elasticities were highest for energy (except for US where it was second highest after capital); meaning that in industrial economies, energy comprises the most significant production factor. This work enriches such studies via integrating the analysis all forms of capital and for a wider range of countries; estimating the trade-off –as output elasticity ratios- between the accumulation of various anthropogenic capital forms and the deterioration of natural capital –considered both as resource stock and carrying capacities of the environment.

Keywords: energy, fossil fuels, industrial civilization, capital, production factor, natural capital, 2nd Law, entropy, irreversibility, exergy, LINEX function, output elasticity

Contribution of the Project

The world economy massively transforms natural resources and accumulates surplus wealth in the form of *capital*. The project examines for four aggregate country groups the **substitutability** between *natural* and *anthropogenic* capital in the context of *Genuine Savings*, which is a measure of **net capital accumulation**.

1. Energy, power and civilization

The measure of human civilizations' evolution is the net increase in their ability to generate *physical work* and harness its *power*, both based on the universal concept of *Carnot Heat Engine*. The process of substituting labor with energy though, comes at the cost of *irreversible* depletion of natural stocks due to the *2nd Law*.

$$\eta = 1 - (T_C / T_H)$$

η = Heat Engine efficiency, **η ε(0,1)**

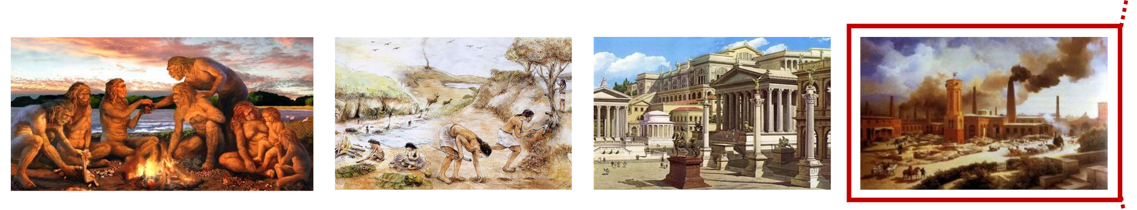
T_C = Temperature of **cold tank** (in K)

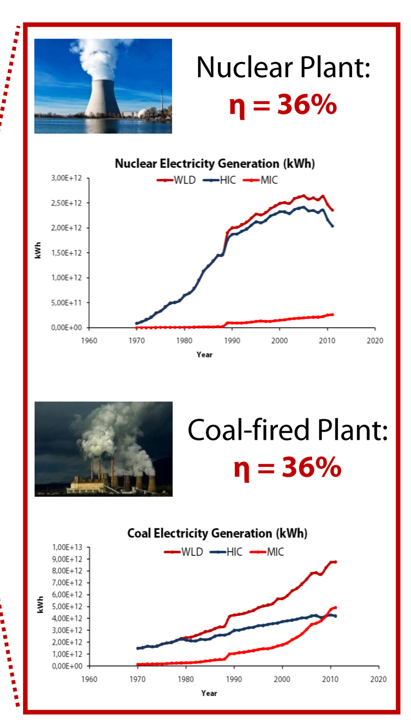
T_H = Temperature of **hot tank** (in K)

Daily energy budgets per capita (based on *Kümmel 2011*):

- ✓ Gatherers' (fruits, vegetables) Society = **2 kWh/d**
- ✓ Hunters' Society ~**3-4 kWh/d** (without fire)
- ✓ Hunters' Society ~**6 kWh/d** (with fire)

Primitive Societies (Muscle heat engines)



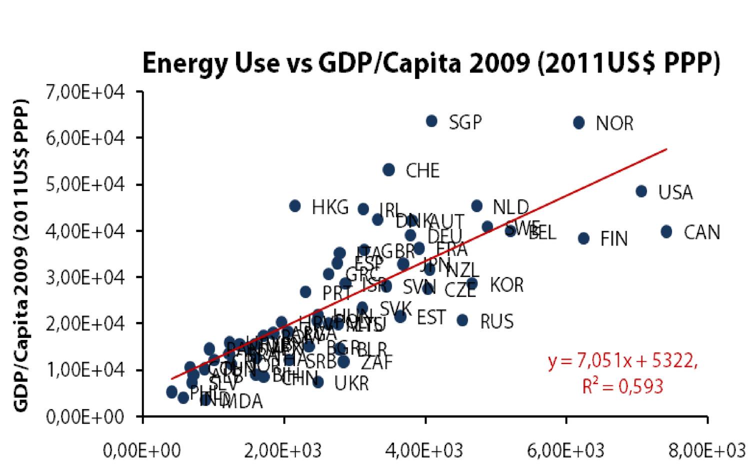


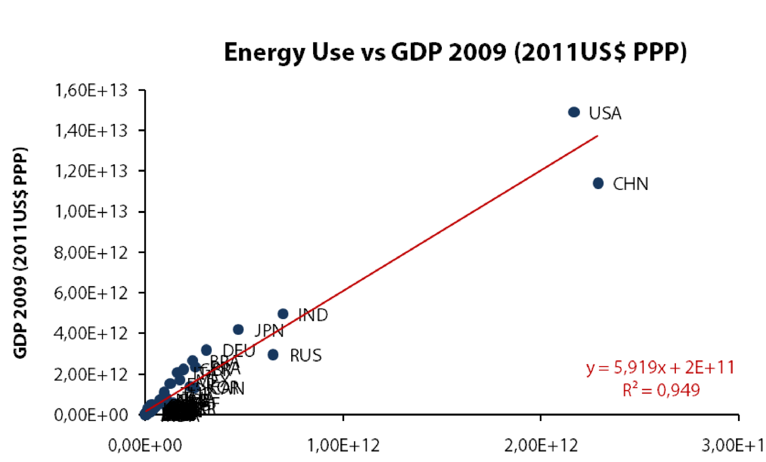
- ✓ Classical and Roman Ancestry = **20kWh/d**
- ✓ Middle Ages (1400 AC) = **30 kWh/d**
- ✓ Industrial Revolution (1850 AC) = **76 kWh/d**
- ✓ Modern Electrification Era = **112 kWh/d**

Agricultural Civilization (Biochemical solar input stocks)

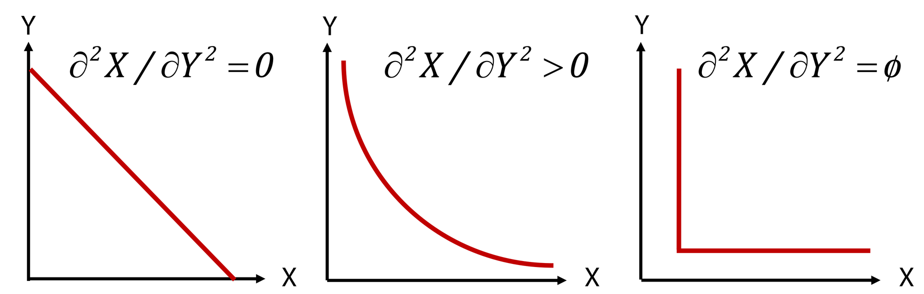
Fossil-fueled Civilization (Fossil solar input stocks)

Per capita and aggregate ability for income and wealth accumulation is highly depended on energy use





2. Energy, capital and substitutability



Case 1: **Perfect Substitution** X and Y substitute each other infinitely

Case 2: **Partial Substitution** X and Y substitute each other finitely

Case 3: **No Substitution** X and Y are useful only in specific ratios

Substitutability and Complementarity

The *Utility Curves* chart the *Marginal Rate of Substitution* (MRS) (trade-off) ratio between two or more conflicting variables (i.e. natural resources depletion vs. mechanical capital accumulation). The main attribute of utility curves is whether they are *substitution or complementary-intensive*; as this impacts the limits of trading-off the two variables.

$$|MRS| = \partial X / \partial Y$$

Instead of the standard MRS, the *MRS Elasticity* is considered more convenient to use as it is independent of effects of scale.

$$|MRS_{Elasticity}| = (\partial X / X)/(\partial Y / Y)$$

The Fundamental Fallacy of the Neoclassical Production Function and the 2nd Law

Economics is called *the science of scarce resources*. The fundamental cause of scarcity is the generation of entropy across every process of natural resource transformation. Neoclassical production functions of *Cobb-Douglas* form with *constant returns to scale* ($a+b+c=1$; $a, b, c>0$; $b>a>c$) do not take into account the limited substitutability between natural and mechanical capital, so that while the *1st Law* is maintained, the *2nd Law* is artificially violated.

Assuming the following Cobb-Douglas production function of 3-variables with output elasticities a, b and c:

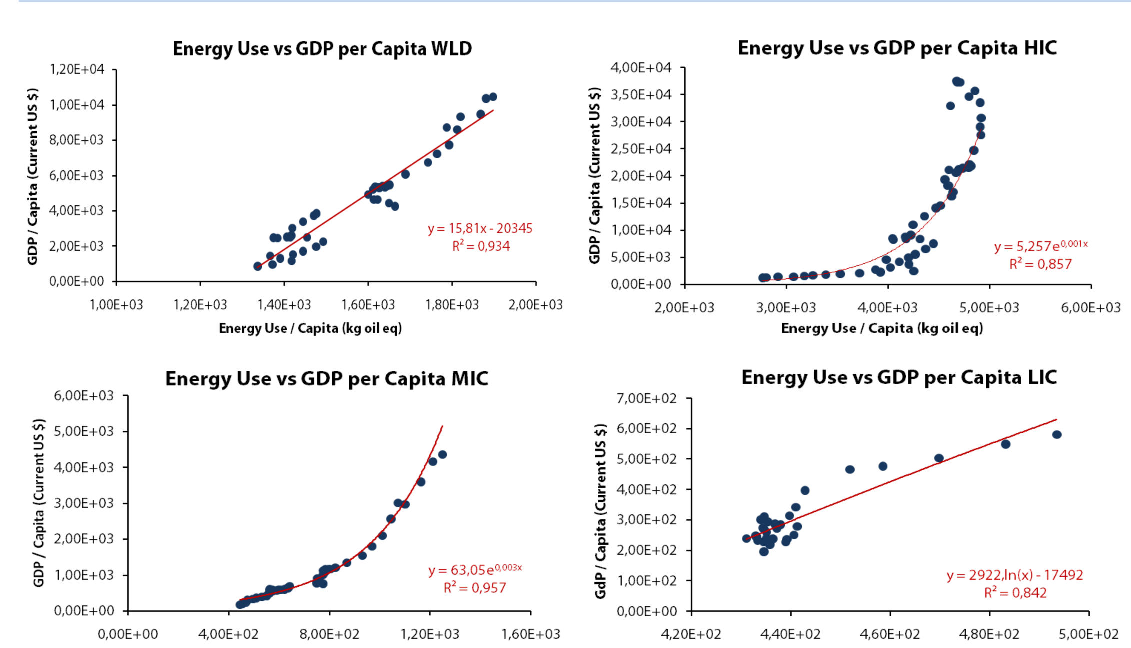
$$Y = R^a \cdot K^b \cdot L^c$$

Y=GDP; **R**=Natural Capital; **K**=Mechanical Capital; **L**=Labor

The paradox lies in that for a constant output Y, and Labor L, we can theoretically increase infinitely mechanical capital K by reducing infinitely natural capital R.

$$R^a = \frac{Y}{K^b \cdot L^c}$$

3. Energy and the evolution of global wealth per capita



Energy and sustainable output

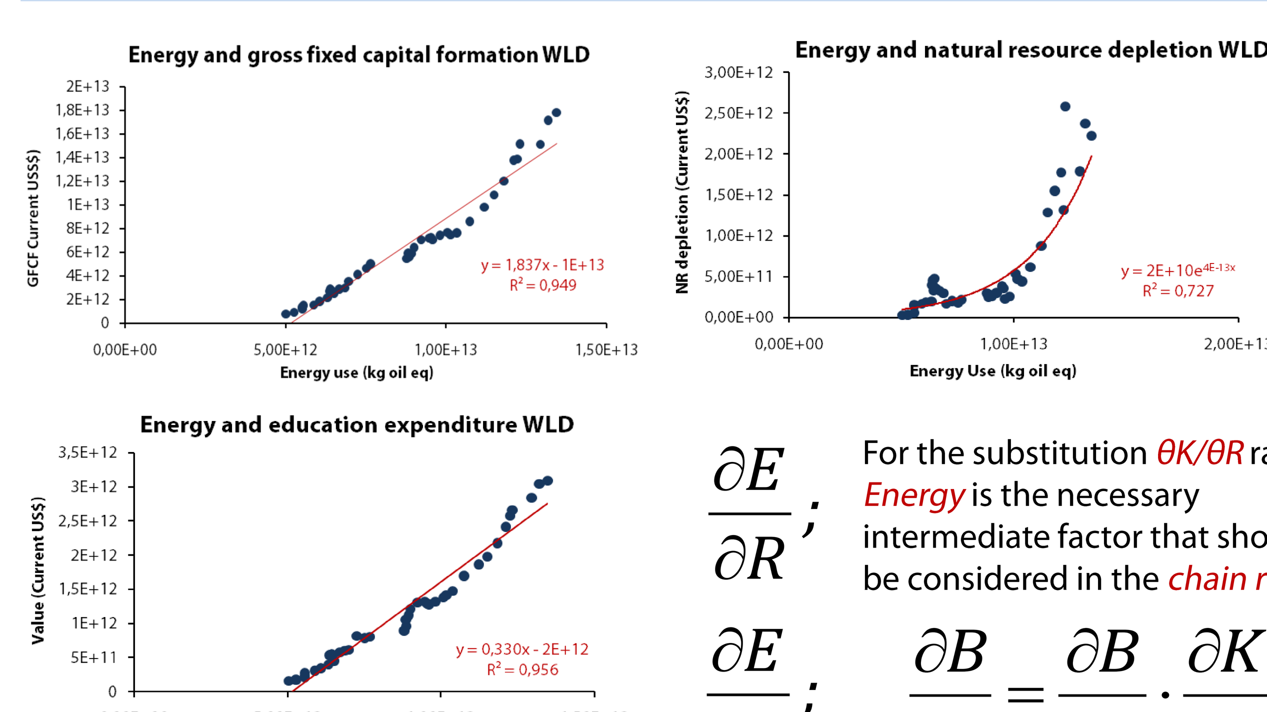
The *GDP* is highly correlated to *Energy Use* in all income groups; *World* (WLD), *High Income Countries* (HIC) *Medium Income Countries* (MIC) and *Low Income Countries* (LIC). However, the GDP does not provide information on the sustainability of output and *substitutability between natural and mechanical capital*.

The LINEX Production Function

It depends *linearly* on energy and *exponentially* on the output elasticity ratios of production factors; hence assuming *limited substitutability*.

$$y = y_0 \cdot e \cdot exp\left[a\left(2 - \frac{l+e}{k}\right) + a \cdot c\left(\frac{l}{e} - 1\right)\right]$$

4. Energy and capital growth sustainability: Adjusted Net Savings



Concept of the ANS

It incorporates the effect of *natural capital depletion* across *mechanical capital accumulation*. By *Hartwick's Rule (1977)*, natural capital depletion is compensated via investment of rents in *human capital* (B).

$$\frac{\partial E}{\partial R};$$

For the substitution *∂K/∂R* ratio, *Energy* is the necessary intermediate factor that should be considered in the *chain rule*.

$$\frac{\partial K}{\partial R} = \frac{\partial K}{\partial E} \cdot \frac{\partial E}{\partial R}$$

$$\frac{\partial E}{\partial R}; \quad \frac{\partial B}{\partial R} = \frac{\partial B}{\partial K} \cdot \frac{\partial K}{\partial R} = \frac{\partial B}{\partial K} \cdot \left(\frac{\partial K}{\partial E} \cdot \frac{\partial E}{\partial R}\right)$$

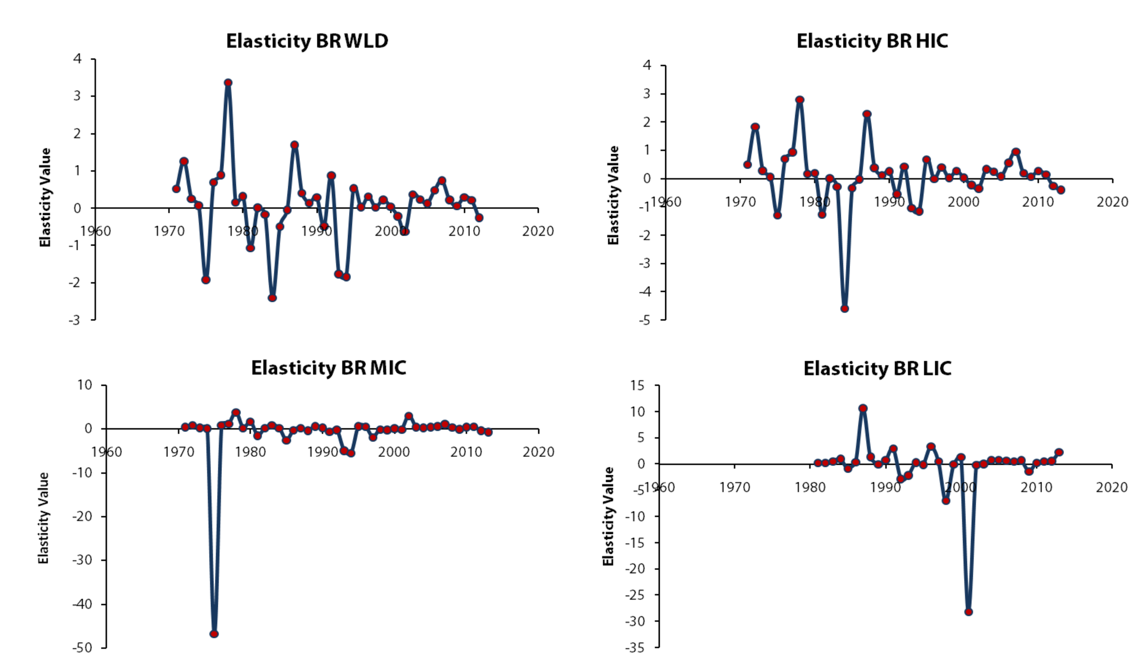
5. Energy and substitution elasticities of capital forms

The elasticity of substitution *between Human Capital* (*B*) and (depleted) *Natural Capital* (*R*) is:

$$\varepsilon_{BR} = \varepsilon_{BK} \cdot \varepsilon_{KR} = \varepsilon_{BK} \cdot \varepsilon_{KE} \cdot \varepsilon_{ER}$$

The elasticities of substitution for all capital forms *B*, *K* and *R* are fully developed with the chain rule:

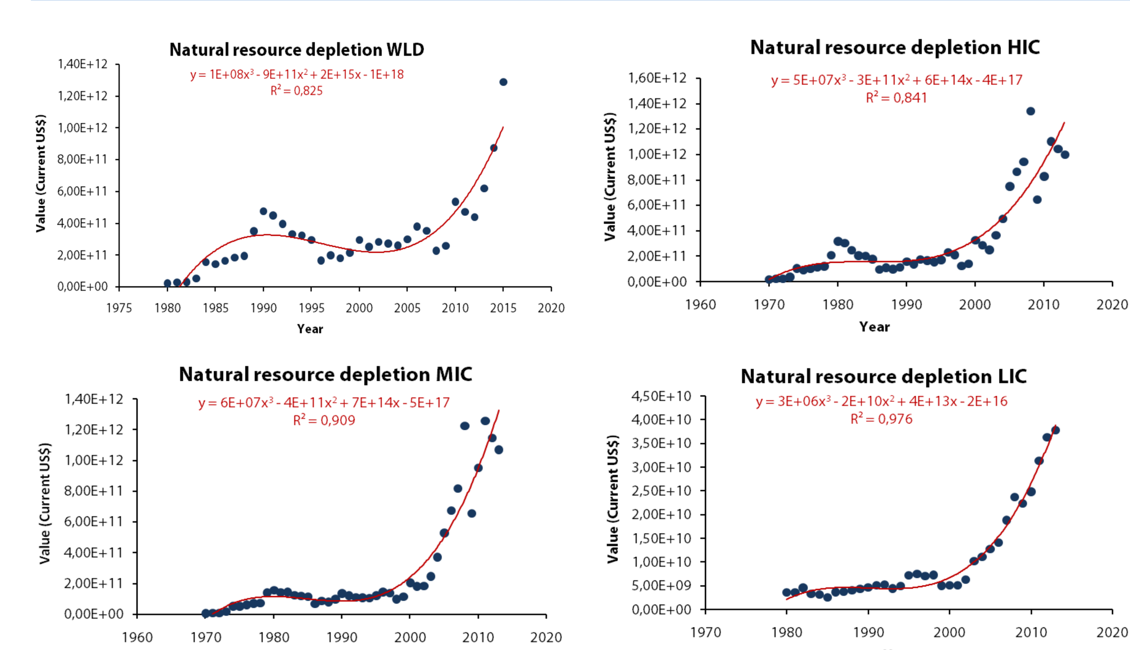
$$\frac{(\partial B / B)}{(\partial R / R)} = \frac{(\partial B / B)}{(\partial K / K)} \cdot \frac{(\partial K / K)}{(\partial R / R)} = \frac{(\partial B / B)}{(\partial K / K)} \cdot \left(\frac{(\partial K / K)}{(\partial E / E)} \cdot \frac{(\partial E / E)}{(\partial R / R)}\right)$$



Endogenous growth limits

The effect of *human capital* (education) expenditures – as compensation to natural capital depletion- emerge with *time-lags*. That explains the *sequence of signs* of the substitution elasticities. In the *long-term*, elasticities *tend to zero* (WLD and HIC), as the quantitative effect of natural capital depletion prevails upon the value effect of human capital, in accordance to the *2nd Law*.

6. Energy, natural capital depletion and the Jevons Paradox



The Jevons' Paradox

It suggests that in the *long-term*, all efficiency effects are cancelled out by *absolute increase* of resource depletion (due to a population increase or higher affordability of new technologies). The paradox is modeled via a *3rd degree polynomial* and confirms the findings on *substitution elasticity decrease*; mostly for WLD and least for LIC.

7. Conclusions

- ✓ Exergy availability has been driving human civilization evolution via large-scale substitution of human labor, and the ability to *accumulate future production ability* in form of *capital*.
- ✓ Energy use and gross economic output of modern economies are *highly correlated*.
- ✓ Natural resource depletion is a prerequisite of wealth generation and is based on the *2nd Law*.
- ✓ As natural resources embody all the *possible manifestations of wealth* (either material or immaterial), they are considered as the stock of *natural capital*.
- ✓ Across the process of natural capital transformation to mechanical capital it is important to know the degree of *substitutability* and *complementarity*.
- ✓ As total capital is not adequately reflected in the GDP, the *Adjusted Net Savings (ANS)* has been developed as an integrated indicator of *natural*, *mechanical* and *human capital*.
- ✓ The *scarcity rents* from natural capital depletion should be *invested in human capital*.
- ✓ The *substitution elasticities* tend in the long-term asymptotically to *zero*; highlighting the *Jevons Paradox* and the long-term prevalence of the 2nd Law.

Sign Nomenclature

Progress Report

Conceptualization: Indicates a conceptual scheme or a theoretical visualization of an important energetic process

Complex System: Indicates the presence of a complex system across the performance of an energetic process

About the Author

Georgios Karakatsanis is an economist; graduate of ***Athens University of Economics and Business (AUEB)***, from which he received training in the field of *International Economics*. He continued his studies in ***National Technical University of Athens (NTUA)***, from which he gained a MSc. in the field of *Environment and Development*. Currently he is a joint PhD Candidate in ***NTUA*** and ***Technische Universität München (TUM)***. His core research interests are: energy, water resources, economic development and growth, innovation finance, economic complexity, economic geography, econometrics and agriculture. His area of interest is Africa, with Ethiopia as his focus country, which experiences its first historical phase of development and industrialization via rapid increase of energy use.

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