



Energy as a limiting factor of economic growth: the profit rate channel

Alban Pellegris

► To cite this version:

| Alban Pellegris. Energy as a limiting factor of economic growth: the profit rate channel. 2023. <hal-04120296>

HAL Id: hal-04120296

<https://univ-rennes2.hal.science/hal-04120296v1>

Preprint submitted on 7 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Energy as a limiting factor of economic growth: the profit rate channel

Alban Pellegris – Working Paper

1. Introduction

Neoclassical economists do not consider energy as an important driver of economic growth. In their perspective, economic growth comes from the accumulation of different capitals: technical capital, human capital, technological capital or public capital. Energy resources are also a capital: they belong to the so called *natural capital*. However, this capital is not specific so that, in the long run, it appears to be substitutable by other capitals (Solow, 1974; Stiglitz, 1974).

Ecological economists have vigorously opposed these views in many ways. Two major contribution are the *neo-thermodynamic theory of growth* developed by Robert Ayres and Benjamin Warr (Ayres and Warr, 2009) and the *biophysical approach* developed by Cleveland and Hall (Cleveland et al., 1984; King and Hall, 2011).

For Ayres and Warr and their followers (Santos et al., 2018), the measurement of energy from useful exergy allows the Solow residual to disappear. Thus energy would explain most of the 20th century economic growth. However, the fragility of this approach lies precisely in the analytical framework in which it is situated. It falls under the same post-Keynesian criticism formulated during the Cambridge controversy towards Agregate Production Function (Felipe and McCombie, 2014; Robinson, 1953; Sraffa, 1963). In other words, the physical and monetary dimensions of production are not distinguished but rather confused (Hornborg, 2014; Pellegris, 2022).

Faced with these limitations, the *biophysical approach* may appear more robust. According to these authors, economic development depends on the energy surplus, which directly rely on the EROI. To prove this, they establish a relationship between the EROI, the price of energy, the energy bill and thus the GDP. The mechanism can be summarized in the following figure:



Fig 1. Energy surplus as a limiting factor to economic growth

Source: author

According to these economists, the EROI determines the price of energy (Heun and de Wit, 2012) while the price of energy would, for a given energy intensity of GDP, affect the weight of the energy bill¹. Finally, an increasing energy bill would subtract sums used for consumption or investment and reduce the rate of economic growth (Bashmakov, 2007; Fizaine and Court, 2016; Murphy and Hall, 2011). For example, in the US case, Fizaine and Court (2016) estimate that the maximum bill to expect positive economic growth is 11%, which would correspond to an EROI of 11:1.

However, this litterature has two limitations. Firstly, this work is (implicitly) based on the energy theory of value (Costanza, 1980; Farber et al., 2002). Although not always explicitly claimed (Pirgmaier, 2021), the EROI does correspond to the energy embodied in energy production. Yet this theory of value has been criticised for its substantialism and reductionism (Hornborg, 2014).

¹ Indeed, the energy bill in relation to GDP can be expressed as the product of the energy price (p) and the energy intensity (E/GDP). $\text{Energy bill/GDP} = p * E/\text{GDP}$

Secondly, this work is questionable in terms of the method used. While the channel identified is a demand channel (the weight of the bill affects consumption and investment), the model used by Court and Fizaine (2016) take capital and labour, two supply variables, as the control variables. The model used does not therefore allow for a proper test of the hypothesis, which weakens the significance of the results.

In this paper, we argue that these difficulties can be overcome by turning to another paradigm: Marxist political economy. Thus, this paper can be understood as part of a collective movement to restore the Marxist perspective within the ecological economics (Burkett, 2004; Foster and Burkett, 2004; Pirmmaier, 2021). To show this we proceed in three steps. Section 2 shows that the Marxist framework allows us to theoretically identify a *profit rate channel* through which energy exerts a limiting character on the growth process. Sections 3 and 4 propose an empirical evaluation of this channel: section 3 presents our method while section 4 presents and discusses the results. Section 5 concludes.

2. The theoretical existence of a profit rate channel

Three elements structure the Marxist framework: (1) the adherence to the labour theory of value (2) the importance of the rate of profit in the economic dynamic, especially (3) the equalization of profit rate among industries. Let us see how these concepts are articulated to think about the limiting character of energy on the growth process.

2.1. The labor theory of value

Summarized briefly, the labour theory of value considers that the relative prices of goods are given by the quantities of labour (direct and indirect) that the goods incorporate. This theory therefore makes room for natural constraints: the more difficult goods are to produce, the higher the relative price will tend to be. From this point of view, the labour embodied in the production of energy is therefore a possible alternative to the EROI (embodied energy) to account for the price of energy.

Contrary to the energy theory of value, the labor theory of value is still discussed and some recent work have shown its relevance (Cockshott et al., 1995; Cockshott and Cottrell, 2005; Tsoulfidis, 2008; Wright, 2019; Zachariah, 2006) to analyze relative prices dynamics.

2.2. The rate of profit

The rate of profit is a fundamental variable that determines the rate of accumulation, i.e. the rate of growth. Marx analyses the rate of profit as the ratio between two variables:

- the rate of exploitation, which relates the amount of profits (P) to the wage bill (W)
- the organic composition of capital (OCC), which relates the value of constant capital (that is machines and raw materials, C) to the value of variable capital (that is the value of the workforce, W).

$$Profit\ Rate = \frac{\frac{P}{W}}{\frac{C}{W} + 1}$$

The organic composition of capital is not a purely technical indicator, as prices will influence this ratio. Nevertheless, there is a technical component that Marx calls the technical composition of capital (TCC) which relates the quantity of machines (c) to the quantity of workers (L).

$$TCC = \frac{c}{L}$$

If we add to the analysis, pc the unit price of capital and w the individual wage, the OCC can be expressed by the following equation:

$$OCC = \frac{c}{L} * \frac{pc}{w}$$

$$OCC = TCC * \frac{pc}{w}$$

Thus, because it is a component of constant capital, when the price of energy increases, all else being equal, the price of constant capital (pc) increases. The organic composition increases, especially in the sectors where the technical composition (CTC) is the highest.

2.3. The equalization of profit rates among industries

This has two consequences: the most capital-intensive branches experience a fall in their profit rate, which drives the average profit rate of the economy down. However, this situation is not sustainable: in order for the capitalists in these industries to continue to produce, a change in relative prices must take place, otherwise they would have an interest in investing in industries with a less capital-intensive technical composition, as the rate of profit is currently higher there. Through this mechanism of capital reallocation, producing relative price movements, profit rates tend to equalize among industries. At the end of this process, all industries, whether intensive or not, gradually tend to align themselves with the new et lower (average) macroeconomic profit rate. The fall in the macroeconomic rate of profit is thus spread and borne by all branches of production

Figure 2 summarize what we call the profit rate channel:

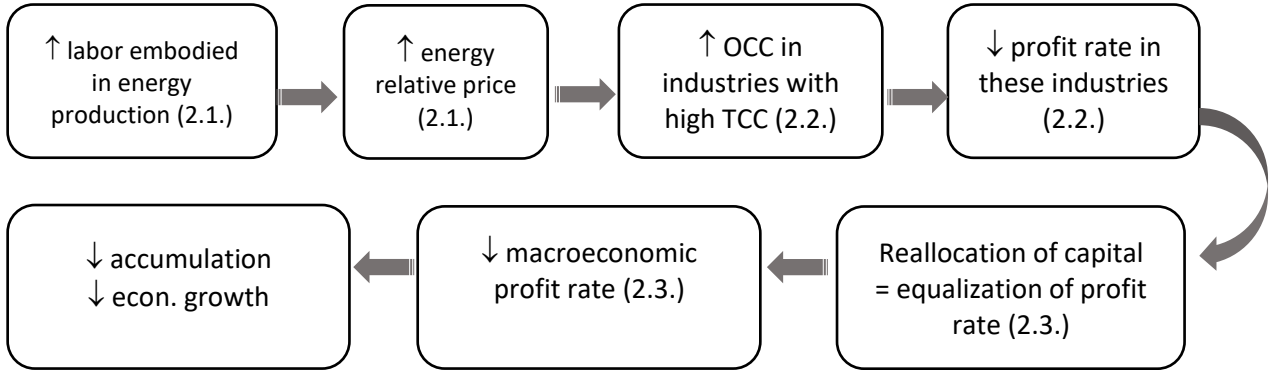


Fig.2 Energy as a limiting factor to economic growth : the profit channel

Sections 3 and 4 propose to verify empirically the existence of this profit rate channel.

3. Methods

In order to test the existence of the profit channel, we develop an econometric analysis of the relationship between the relative price of energy and the profit rate based on a panel of 16 countries over

the period 1995-2019. Our starting hypothesis is that there is a significant and negative relationship between the relative price of energy and the profit rate of an economy.

3.1. Variables

We retain four variables to carry out this econometric work: a dependent variable that we seek to explain, the profit rate, and three explanatory variables. Among these three variables, we find, first of all, the relative price of energy, which is the variable of interest to us and whose influence on the profit rate we are trying to understand. To this variable, we have added two control variables, which are highly likely to influence the rate of profit according to the Marxist perspective mentioned above: the *exploitation rate* and the *technical composition of capital*. First, the exploitation rate, since this is the numerator of the rate of profit formula (see above). A fall in the rate of profit can be compensated by an increase in the exploitation of workers, that is, in the share of value added accruing to capitalists. This is one of the counter-tendencies identified by Marx to the tendency of the rate of profit to fall (Marx, Cohen-Solal and Badia, 1959). Second, the technical composition is also important as suggested in section 2: the effect of the energy price on the profit rate depend on how capital intensive is the industry or the country under study.

3.2. Data

All the data come from the OCDE database. Following the example of other Marxist works (Basu, 2017), the rate of profit series were obtained by relating the *net operating surplus* to the *net value of capital*. For the relative price of energy, we relate the *energy price index* to the *consumer price index*. When the energy price increases faster than the consumer index, the relative price of energy increases. For the exploitation rate, we relate the net operating surplus to the payroll.

The main innovation in terms of indicators relates to the *technical composition of capital*. Following Giampietro et al. (2011), we considere that the capital intensity of an industry can be observed from the *energetic metabolic rate* (EMR) which relates the quantity of (primary) energy to the hours of work mobilized. Such a ratio offers the advantage to be truly technical in the sense that it does not rely on monetary aggregates but only on physical aggregates.

3.3. Linear regressions and estimators

Once the data are computed, we test the stationarity of our variables (see appendix 6.1.) before running multivariate linear regressions. We first run different models in order to confirm the number of explanatory variables to use (table 1). The result of these four pool OLS confirm the relevance of model D with all three explanatory variables (table 2).

Model	Equation
A	$ProfitRate = \alpha + \beta1PR_{NRJ} + \varepsilon$
B	$ProfitRate = \alpha + \beta1PR_{NRJ} + \beta2Expl + \varepsilon$
C	$ProfitRate = \alpha + \beta1PR_{NRJ} + \beta2TCC + \varepsilon$
D	$ProfitRate = \alpha + \beta1PR_{NRJ} + \beta2Expl + \beta3TCC + \varepsilon$

Table 1. Different equations estimated

With α , a constant ; $\beta1$, $\beta2$ et $\beta3$ coefficients of the explanatory variables explicatives and ε the error term. PR_NRJ = relative price of energy; Expl = exploitation rate; TCC = technical composition of capital. Source : auteur

Modèles

	A	B	C	D
Constant	13.44 *** (1.05)	6.36 *** (0.70)	14.84 *** (1.01)	7.04 *** (0.73)
Relative Price of energy	-5.70 *** (1.12)	-4.76 *** (0.69)	-4.89 *** (1.07)	-4.56 *** (0.68)
Exploitation rate		0.12 *** (0.00)		0.12 *** (0.00)
Technical composition of capital			-0.33 *** (0.05)	-0.10 ** (0.03)
R²	0.06	0.65	0.16	0.66
Adjusted R²	0.06	0.65	0.16	0.66
Number of observations	400	400	400	400
*** p < 0.01 ; ** p<0.05 ; * p<0.1				

Table 2. Pool OLS with the different explanatory variables.

Source : auteur.

In a second step, we consider four econometric regressions that complement the last one (Pool OLS) that we have just presented. These new regressions allow us to confirm the robustness of our approach, as do Carpenter and Guariglia (2008) for an estimation of fixed capital accumulation on panel data. In the end, we report in Table 3 the following 5 regressions for our tri-variate equation:

- 1- A pool model with an OLS estimator (Pool Ordinary Least Square) where all our data are treated as a single geographic set. This model has already been estimated since it is the result of equation D, a model that will be called "Pool" in the following.
- 2- A country fixed effect model with *within estimator* ("Country" model) where the regression is conducted for each of the 16 countries. A fixed effect model means that "the difference between individuals can be captured by the constant" (Greene et al., 2011, p.345). Here, the estimated model will therefore have a different constant for each of the 16 countries.
- 3- A time fixed effect model with *OLS estimator* ("time" model) where the regression is conducted for each year. Example: we compile all the data from all the countries for the year 1995 and we look at the relationship that emerges. Unlike the previous model, there is not a constant for each country but for each year selected.
- 4- A model with country and time fixed effects with OLS estimator ("two effects" model) which combines the two previous models since we control here both the country and the year.
- 5- A random model with a random estimator: like a fixed-effect model, a random model will consider that being in country A, rather than in country B, will affect the relationship between profit and energy price. However, unlike the fixed-effect model, the random-effect model considers that it is possible for countries to respond differently to a change in energy price. In statistical terms, the relationship is not just affected by a different constant.

4. Results

4.1. Results of multivariate regressions

	Models				
	« Pool »	« Country »	« Time »	« Two ways »	« Random »
Constant	7.04 *** (0.73)		9.86 *** (1.23)	3.77 *** (0.76)	5.58 *** (0.64)
Relative price of energy	-4.56 *** (0.68)	-3.4 *** (0.34)	-8.71 *** (1.44)	-1.00 (0.08)	-3.43 *** (0.34)
Exploitation rate	0.12 *** (0.00)	0.09 *** (0.01)	0.12 *** (0.00)	0.08 *** (0.01)	0.09 *** (0.01)
Technical composition of capital	-0.10 ** (0.03)	0.21 *** (0.04)	-0.09 ** (0.03)	0.24 *** (0.04)	0.19 *** (0.04)
R²	0.66	0.50	0.68	0.94	0.50
Adjusted R²	0.66	0.48	0.65	0.93	0.50
Number of observations	400	400	400	400	400

*** p < 0.01 ; ** p < 0.05 ; * p < 0.1

Table 3. Results of multivariate regression of the rate of profit on the relative price of energy, the operating rate and the technical composition of capital.

Source : author

We can first note that, with the exception of the "two-effects" model, whatever the model chosen, our variables are all significant. For all these other models, our independent variables are not only significant, but above all the coefficients are compatible with our hypotheses:

- The increase in the price of energy tends to negatively affect the profit rate ("country," "time," "random" and "pool" models)
- The exploitation rate tends to affect the profit rate positively (all models)
- The increase in the technical composition of capital tends to affect the rate of profit negatively ("pool" and "time" models) or positively ("random", "country", and "two effects" models)

To choose between these different models, we run several tests (see appendix 6.2.). First, we distinguish a pool OLS pool from a country fixed effect model. In our case, it seems reasonable to consider a country fixed effect. Indeed, we can estimate that there are unobservable variables, specific to each of the countries studied. For example, some countries have a particular position in the value chain that allows for a higher profit rate than elsewhere, as the analysis of profit rates has revealed. The use of a Fisher test confirms this intuition and highlights significant effects linked to heterogeneity between countries.

We then determine whether a country fixed effect model should be preferred to a random effect model. To do this, we perform a Hausman test. With a p value < 0.05, this test leads us to prefer the fixed effect model. Finally, we need to decide whether the country fixed effects should be combined with a year fixed effect ("two way fixed" model). Here again, there is a test to guide us: the Lagrange multiplier test for time effect (Breusch-Pagan) for cylindrical panels. With a p-value > 0.05, this test leads us to prefer the model with only a country fixed effect. Finally, a last comparison must be made: that between a model with time fixed effects and a model with country fixed effects. The Fisher test allows us to decide in favor of the country fixed effects model.

Finally, we test different characteristics that can modify the robustness of the selected model. Our data exhibits heteroskedasticity, serial correlation and cross sectional dependence (see appendix 6.3.). According to Baltagi (2021), autocorrelation and cross-sectional dependence can be problematic

for macroeconomic panels with large time series (beyond 20 to 30 years). Since our study covers a 24-year period and our data are macroeconomic, we consider a procedure to take care of their presence. Heteroscedasticity also makes the estimates provided by the least squares method questionable (our various estimators are all derived from this method). The econometric literature suggests two different ways to take into account the behavior of model errors.

The first solution consists in keeping a model using the least squares method (Ordinary Least Square) but with *robust standard errors* (Bai et al., 2020). In the case where heteroscedasticity, autocorrelation and dependence between sections are present, Hoechle (2007) recommends using the Driscoll-Kraay estimator.

The second solution proposed by Bai et al. (2020) is to use an FGLS (Feasible Generalized Least Square) model when the number of years T is greater than the number of individuals N, which corresponds to our situation (T= 25 and N=16). This type of model allows estimation in the presence of autocorrelation, dependence between sections within the panel and heteroscedasticity across the panel.

It is clear that taking into account autocorrelation, heteroscedasticity and dependence between sections does not change our results. Both methods (Discroll & Kray and FGLS) give us significant coefficients (table 4)

	« Country »	Models « Discroll & Kray »	« FGLS »
Relative price of energy	-3.4 ***	-3.4*	-3.4***
Exploitation rate	0.09 ***	0.09*	0.09***
Technical composition of capital	0.21***	0.21***	0.21***
R²	0.50	0.50	0.39
Adj. R²	0.48	0.48	
Number of observations	400	400	400
*** p < 0.001 ; ** p<0.01 ; * p<0.05			

Table 4. Results of 3 models : fixed effect, Discroll & Kray and FGLS.

Source : author

4.2. Interpretation

The estimation of the two models is consistent with our hypotheses. The relative price of energy appears to be negatively correlated with the profit rate. The coefficient is -3.4. This means that when the relative energy price index increases by one unit, then the profit rate decreases by 3.4 percentage points. The interpretation of one unit of relative price is not immediately obvious. To understand it, we need to recall the values of relative prices: the relative price of energy ranges from about 0.75 to 1.10, between 1995 and 2019, for all countries combined. The change in the relative price of energy over the period is therefore less than one unit. The increase of one unit represents, in the case of a relative price of 0.75, an increase of 130%. Over the period studied, the energy price index increased by only 0.35 units, or about 46%. If we accept a rough calculation, it turns out that the increase in the relative price of energy would have cost $0.46 \times 3.4 = 1.19$ points of profit rate between 1995 and 2019. The effect therefore appears to be substantial over the period.

We can say that this empirical work largely validates the hypotheses formulated by the Marxist analytical framework. The latter thus appears heuristic in order to understand the way in which energy, an indispensable use value in the economy, exerts its effects on the dynamics of growth. In particular, we highlight a profit rate channel that, until now, seems to have been neglected by the literature in ecological economics which prefers the weight of the energy bill. Controlling for the exploitation rate

and technical composition of capital, the effect of the relative price of energy is significant on the rate of profit, confirming the hypothesis of an action through the organic composition of capital.

4.3. Energy bill as part of the profit rate channel

It is possible to put this opposition between the rate of profit and the weight of the energy bill into perspective. Indeed, if we examine the formula of the weight of the energy bill in GDP, it is possible by rearranging the equation to include the variables we have used in our regression.

$$EB = \frac{\text{Energy bill}}{nGDP}$$

$$EB = \frac{Pe * Qe}{nGDP}$$

$$\text{and } nGDP = P * rGDP$$

$$\text{So } EB = \frac{Pe}{P} * \frac{Qe}{rGDP}$$

$$\text{And } \frac{Qe}{rGDP} = \frac{Qe}{h} * \frac{h}{rGDP}$$

So that :

$$EB = \frac{Pe}{P} * \frac{Qe}{h} * \frac{h}{rGDP}$$

EB : energy bill/GDP

nGDP : nominal GDP ; rGDP : real GDP

Pe : energy price; P : price; Pe/P : energy relative price

Qe : energy quantity; h : hours worked ; Qe/h : technical composition of capital

rGDP/h : real productivity of labor

The profit rate channel exhibits two control variables that are part of the definition of the energy bill. This could explain why, in the case of France, Marxist authors like Husson (2009) observe a high correlation between the energy bill and the profit rate (fig.3). It also confirms that the energy bill can be used in a supply channel (the profit rate channel) rather than a demand channel (as suggested by the biophysical approach).



Fig.3 Energy bill (as % of GDP) and the profit rate, France (1949-2006).

Taux de profit = profit rate; consommation d'énergie en valeur (% du PIB) = energy bill (% of GDP)

Source : Husson 2009

5. Concluding remarks

In this article, we have shown the heuristic character of the Marxist framework to show how energy acts as a limiting factor in the growth process. This framework makes it possible to identify a supply channel, the rate of profit channel, which appears more robust than a demand channel, the energy bill channel, highlighted by the authors of the biophysical approach. Indeed, the statistical work conducted on data from a panel of 16 OECD countries confirms the existence of this channel over the period 1995-2019. In contrast to the work of the biophysical approach, the control variables used are consistent with the hypothesis tested. Moreover, the reformulation of the energy bill (as a product of three factors: the relative price of energy, the technical composition and real labor productivity), suggests that the energy bill can also be interpreted in the context of a supply channel.

An interesting extension of this work would be to compare the results in terms of labor embodied in energy production with those in terms of energy embodied in energy production (EROI).

6. Appendix

6.1. Unit root tests

	Augmented Dicker-Fuller (1 lag)			Interpretation
	Constant			
Profit rate	-4,1844***			Stationary
Relative price of energy	-65663**			Stationary
Exploitation rate	-4,805***			Stationary
Technical composition of capital	-3,5101**			Stationary
	Levin Lin Chu (1 lag)			Interpretation
	Constant	Constant + trend	/	
Profit rate	-3,2144***	-2,9165***	-3,32256***	Stationary
Relative price of energy	-2,1194**	-1,8362**	3,0059	Stationary
Exploitation rate	-3,1422***	-3,352***	-2,0758***	Stationary
Technical composition of capital	-1,8568	-2,6043***	-3,5665***	Non Stationary
	Maddala et Wu (lag=AIC)			Interpretation
	Constant	Constant + trend	/	
Profit rate	548,28***	714,19***	112,54***	Stationary
Relative price of energy	411,66***	1007,2***	17,178	Stationary
Exploitation rate	646,12***	1129,7***	48,399**	Stationary
Technical composition of capital	258,63***	711,43***	240,32***	Stationary

*** p<0,001, ** p<0,05 et * p<0,1

Table 5. Unit root tests

Source : author

6.2. Tests to decide between the different models

Goal/comparison	Test	H0	Result	Interpretation
« Pool » VS « country »	Fisher	« Pool » > « country »	92,087***	« Country » > « Pool »
« country » VS « random »	Haussman	« Aléatoire » > « country »	11,987***	« Country » > « Random »
« country » VS « two ways »	Lagrange multiplier	Pas d'ajout nécessaire	3.5472*	“Country” > “two ways”
“Country” VS “time”	Fisher	“Country” > “time”	-31,913	“Country” > “time”

Avec *** p < 0.01 ; ** p<0.05 ; * p<0.1

Table 6. Results of the various tests used to distinguish the models. Source : author

6.3. Heteroskedasticity, auto-correlation and cross sectionnal dependance

Objectif	Test	H0	Result	Interpretation
Heteroskedaticity	Breush-Pagan	Homoskedaticity	88.522*** (BP)	Heteroskedaticity
Auto-correlation	Breush-Goodfrey-Woolridge	No auto-corrélation	264,89*** (chisq)	Auto-correlation
Cross-sectionnal dependance	Breush-Pagan LM	No dependance	586,4*** (chisq)	Cross-sectionnal dependance
Cross-sectionnal dependance	Pesaran CD	No dependance	5,544*** (z)	Cross-sectionnal dependance
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$				

Table. 7 Testing for heteroscedasticity, autocorrelation and cross-sectional dependence.
Source : author

7. References

- Ayres, R.U., Warr, B., 2009. The economic growth engine: how energy and work drive material prosperity. Edward Elgar Publishing Ltd, Cheltenham.
- Bai, J., Choi, S.H., Liao, Y., 2020. Feasible Generalized Least Squares for Panel Data with Cross-sectional and Serial Correlations. *Empirical Economics* 309–326.
- Baltagi, B.H., 2021. *Econometric Analysis of Panel Data*, Springer Texts in Business and Economics. Springer, New-York.
- Bashmakov, I., 2007. Three laws of energy transitions. *Energy Policy* 35, 3583–3594. <https://doi.org/10.1016/j.enpol.2006.12.023>
- Basu, D., 2017. Quantitative empirical research in marxist political economy: a selective review. *Journal of Economic Surveys* 0, 1–28.
- Burkett, P., 2004. Marx's reproduction schemes and the environment. *Ecological Economics* 49, 457–467. <https://doi.org/10.1016/j.ecolecon.2004.02.007>
- Cleveland, C.J., Costanza, R., Hall, C.A.S., Kaufmann, R., 1984. Energy and the U.S. Economy: A Biophysical Perspective. *Science* 225, 890–897. <https://doi.org/10.1126/science.225.4665.890>
- Cockshott, P., Cottrell, A., Michaelson, G., 1995. Testing Marx: Some new results from UK data. *Capital & Class* 19, 103–130. <https://doi.org/10.1177/030981689505500105>
- Cockshott, W.P., Cottrell, A., 2005. Robust correlations between prices and labour values: a comment. *Cambridge Journal of Economics* 29, 309–316. <https://doi.org/10.1093/cje/bei015>
- Costanza, R., 1980. Embodied Energy and Economic Valuation. *Science* 210, 1219–1224. <https://doi.org/10.1126/science.210.4475.1219>

- Farber, S.C., Costanza, R., Wilson, M.A., 2002. Economic and ecological concepts for valuing ecosystem services. *Ecological Economics* 41, 375–392. [https://doi.org/10.1016/S0921-8009\(02\)00088-5](https://doi.org/10.1016/S0921-8009(02)00088-5)
- Felipe, J., McCombie, J.S.L., 2014. The Aggregate Production Function: ‘Not Even Wrong.’ *Review of Political Economy* 26, 60–84. <https://doi.org/10.1080/09538259.2013.874192>
- Fizaine, F., Court, V., 2016. Energy expenditure, economic growth, and the minimum EROI of society. *Energy Policy* 95, 172–186. <https://doi.org/10.1016/j.enpol.2016.04.039>
- Foster, J.B., Burkett, P., 2004. Ecological Economics and Classical Marxism: The “Podolinsky Business” Reconsidered. *Organization & Environment* 17, 32–60. <https://doi.org/10.1177/1086026603262091>
- Giampietro, M., Mayumi, K., Sorman, A., 2011. *The Metabolic Pattern of Societies: Where Economists Fall Short*. Routledge, Londres. <https://doi.org/10.4324/9780203635926>
- Guariglia, A., Carpenter, R., 2008. Cash flow, investment, and investment opportunities : new tests using UK Panel data. *Journal of banking & finance*. 32, 1894–1906. <https://doi.org/10.1016/j.jbankfin.2007.12.014>
- Heun, M.K., de Wit, M., 2012. Energy return on (energy) invested (EROI), oil prices, and energy transitions. *Energy Policy* 40, 147–158. <https://doi.org/10.1016/j.enpol.2011.09.008>
- Hoechle, D., 2007. Robust Standard Errors for Panel Regressions with Cross-Sectional Dependence. *The Stata Journal* 7, 281–312. <https://doi.org/10.1177/1536867X0700700301>
- Hornborg, A., 2014. Ecological economics, Marxism, and technological progress: Some explorations of the conceptual foundations of theories of ecologically unequal exchange. *Ecological Economics* 105, 11–18. <https://doi.org/10.1016/j.ecolecon.2014.05.015>
- Husson, M., 2009. Un capitalisme vert est-il possible ? [WWW Document]. *Contretemps*. URL <https://www.contretemps.eu/un-capitalisme-vert-est-il-possible/> (accessed 9.23.22).
- King, C.W., Hall, C.A.S., 2011. Relating Financial and Energy Return on Investment. *Sustainability* 3, 1810–1832. <https://doi.org/10.3390/su3101810>
- Murphy, D.J., Hall, C.A.S., 2011. Energy return on investment, peak oil, and the end of economic growth: EROI, peak oil, and the end of economic growth. *Annals of the New York Academy of Sciences* 1219, 52–72. <https://doi.org/10.1111/j.1749-6632.2010.05940.x>
- Pellegris, A., 2022. Le découplage entre la consommation d’énergie et le PIB : questionnements théoriques et évaluations empiriques du rôle de l’énergie dans le processus de croissance économique.
- Pirgmaier, E., 2021. The value of value theory for ecological economics. *Ecological Economics* 179, 1–10. <https://doi.org/10.1016/j.ecolecon.2020.106790>
- Robinson, J., 1953. The Production Function and the Theory of Capital. *The Review of Economic Studies* 21, 81–106.
- Santos, J., Domingos, T., Sousa, T., St. Aubyn, M., 2018. Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960–2009. *Ecological Economics* 148, 103–120. <https://doi.org/10.1016/j.ecolecon.2018.01.008>
- Solow, R.M., 1974. The Economics of Resources or the Resources of Economics. *The American Economic Review* 64, 1–14.

- Sraffa, P., 1963. Production of commodities by means of commodities: prelude to a critique of economic theory. Cambridge University Press, Cambridge (Royaume-Uni).
- Stiglitz, J., 1974. Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths. *The Review of Economic Studies* 41, 123–137.
- Tsoufidis, L., 2008. Price–value deviations: further evidence from input–output data of Japan. *International Review of Applied Economics* 22, 707–724.
<https://doi.org/10.1080/02692170802407668>
- Wright, I., 2019. Marx’s transformation problem and Pasinetti’s vertically integrated subsystems. *Cambridge Journal of Economics* 43, 169–186. <https://doi.org/10.1093/cje/bex068>
- Zachariah, D., 2006. Labour value and equalisation of profit rates: a multi-country study. *Indian Development Review* 1–20.