- Gide 2016 Conference - Strasbourg -

Energy, Materiality and the Economics of Production, Past and Present

Antoine Missemer*

- CNRS, CIRED -

Abstract

In 1979, Nicholas Georgescu-Roegen famously wrote: "matter matters, too". In this way, he emphasized the material foundations of economic activities, and criticized the theories of production whereby materiality was out of scope. In his view, this shortcoming was due to a quantitative (or "arithmomorphic") bias that prevented most economists to take into account the qualitative characteristics of the world. In this paper, I look deeper into Georgescu-Roegen's diagnosis by examining other reasons for this shortcoming (atemporality, homogenization). Because of its various material forms, energy is a typical case: the economists have always felt some discomfort with it. I illustrate this discomfort with two examples in the history of economic thought. And back to Georgescu-Roegen's fund-flow proposal to overcome the common difficulties, I suggest that the next transition to renewable energies, which have peculiar material specifications, might challenge the economics of production both in its standard and in its roegenian shapes.

Keywords: energy, materiality, theory of production, Georgescu-Roegen, fund-flow model, history of economic thought.

JEL Codes: B1, Q3, Q5.

*E-mail: missemer@centre-cired.fr. Address: CIRED - Centre international de recherche sur l'environnement et le développement (UMR 8568 CNRS/ENPC/EHESS/AgroParisTech/CIRAD), 45bis avenue de la Belle Gabrielle, 94736 Nogent-sur-Marne Cedex, France. – A previous version of this paper has been presented at the COLLENER Conference in Paris (Nov. 2015). I particulary thank Catherine Grandclément and Jules Schers for comments on that former draft.

Introduction

Less than ten years after the publication of *The Entropy Law and the Economic Process* (1971), Nicholas Georgescu-Roegen strengthened his theory of production by recollecting that matter is part of the constraints on economic processes. In his 1979 "Energy Analysis and Economic Valuation", he wrote his well-chosen clause "matter matters, too" in order to warn his fellow economists that thermodynamic principles (the entropy law), not only apply to energy (as physicists teach us), but also to matter and raw materials, which are the foundations of the production of commodities. In Georgescu-Roegen's schedule, energy and matter are indeed intertwined: energy comes from mass materials, fossil fuels being a typical instance. During the whole 1970s, Georgescu-Roegen therefore tried to integrate materiality, and its consequences (qualitative specifications and changes, potential perishability), into the economic reasoning. He received indifference, if not disdain. Although economists could have taken the way of considering material flows of resources if they had not make an averse reaction to the *Limits to Growth* 1972 report (see Pottier, 2014, chp. 2), Georgescu-Roegen's warning appeared as a peculiarity, since the economists have always felt some discomfort with materiality.

In its neoclassical form[1], the theory of production is based on the combination of different factors of production (capital, labour, natural resources) with various inputs (raw materials, intermediary goods), to produce commodities (and potential waste). The role of energy and matter in this theory is undetermined; their materiality (physical properties, changing forms, etc.) is simply ignored. As regards energy resources, materiality is however a striking issue. Industrial plants used wood, then coal, then petroleum and electricity. These energy sources (or vehicles) have various materialities: wood and coal are solid, petroleum is liquid, electricity cannot be stored, etc. These differences may have consequences on economic processes (location of activities, market structures, property rights, etc.), then on economic analysis. By disregarding materiality, the neoclassical theory of production neglects some specifications of the economic realm. This diagnosis may raise indignation or theoretical dissatisfaction. But it can find some explanation.

Why did most economists ignore the materiality of economic items in their theory of production? According to Georgescu-Roegen, it is because of a Newtonian tropism that led most economists to focus on homogeneous and measurable quanti-

[1] In the history of economic thought, the theory of production has taken many features. One may think about the classical, the marxian, Sraffa's, Leontief's theories, and so on. I focus on its neoclassical form (from J. B. Clark to Solow, passing through the Cobb-Douglas function), because it is the one Georgescu-Roegen addresses to.

tative variables (see also Mirowski, 1989). Whatever their qualitative specifications, commodities are only goods and services to be sold on markets. As Michel Callon and Fabian Muniesa (2003, p. 199) underline, in economics there is no distinction to make between "a fish sold on the gross market of Marseille" and "a skiing week in the Mountains". Every economic reasoning deals with variations in the quantities of available, produced or consumed commodities. The material characteristics of these commodities are irrelevant, as are their potential changes overtime. This is what Georgescu-Roegen (1971, p. 341) names the "arithmomorphic" bias (see Missemer, 2013, p. 26-27), from which most economists are accused to suffer.

Looking deeper in Georgescu-Roegen's diagnosis, the Newtonian tropism has led to other bias: the search for atemporal laws, and the need for homogenized variables. Basically, taking into account materiality would have two consequences on economics: admitting the heterogeneity of items at a moment of time, and admitting their moving forms. Energy, for instance, may take various forms in an economy at a moment of time; it may also evolves overtime. In other words, theoretically speaking, materiality leads to *static heterogeneity* and *dynamic contingency*. As I further examine, the neoclassical economics of production has not been designed to incorporate such theoretical characteristics. Georgescu-Roegen has proposed an alternative with his fund-flow model of production. It deserves attention. Does it completely address the materiality issue, in particular with regard to all energy resources (from fossil fuels to renewables)? Perhaps not.

In the next sections, I first give details about the search for atemporal laws and the need for homogenized variables that also explain – beyond the arithmomorphic bias – why the neoclassical theory of production has ignored materiality. To do so, I take two examples in the history of economic thought that illustrate the economists' discomfort with the role of energy resources in production processes: the Böhm-Bawerk-Clark-Fisher controversy on capital theory, and the Solow-Stiglitz growth models with natural resources (section 1). I then describe how Georgescu-Roegen tried to build his fund-flow model as an alternative to incorporate materiality in the economics of production (section 2). Finally I point out that the next transition towards renewable energies might reshuffle the cards, since the materiality of sun, wind and tide is much different from the fossil fuels materiality on which past models, including Georgescu-Roegen's, have been built (section 3). The paper ends up with some concluding remarks.

1 Discomfort and hesitations

As commonly stated, economics deals with two main topics: the production, consumption and distribution of wealth on the one hand, and choices between means to achieve ends on the other. These two poles gather both the ancient classical economists' definition and the modern one that stands behind von Mises' praxeology. By examining these topics, most economic theorists are tempted to state universal laws, or atemporal principles that are valid for many economic systems, for all economic agents, whenever and wherever they live. As Georgescu-Roegen mentions:

> The opinion that the choice-function of the *homo œconomicus*, that is, the utility index, adequately represents the economic behavior of any society is still going strong. (Georgescu-Roegen, 1971, p. 344-345)

Accordingly, the foundations of free-trade theories have been the same since Ricardo's *Principles of Political Economy and Taxation* (1817); and Nash equilibrium is mobilized to analyse both current climate negotiations (Eyckmans and Tulkens, 2003) and the everyday life of Medieval citizens (Greif et al., 1994) – *i.e.* the force of economic theory is its plasticity. Economic theorists are therefore engaged in building wide-application principles. Their project is at once positive and normative. In many cases, economics is not only designed to describe past or idealized activities and mechanisms, but also to participate in the public debate and to elaborate economic policy recommendations. In that way, theorists need prospective models to study not solely past but also future dynamics. These models are often stylized and integrated models, with aggregate variables (see for instance Solow's growth models, or DSGE macroeconomic models).

How does materiality articulate with such a theoretical perspective? As mentioned in the introduction, materiality implies material specification (physical properties, potential perishability, etc.). Conceptual categories have then to be refined. As for energy, wood and fossil fuels need to be distinguished, the former being reproducible in a few years, unlike the latter; petroleum has to be distinguished from electricity, the former being able to be stored, unlike the latter, etc. As a result, taking into account materiality implies a disaggregation of the "energy" conceptual category. Is such a disaggregation compatible with easy-to-manipulate integrated models? It is highly doubtful. The "standard" theory of production, as Georgescu-Roegen calls it, is designed to draw long-term and integrated prospective models

helping public policies. It cannot rightly take into account the static heterogeneity of items, which result from their material specifications.

The material heterogeneity of the world at a given point of time – *static heterogeneity* – may be completed by another material heterogeneity, through duration – *historical contingency*. As regards energy again, it evolves overtime. Industrial plants, and the whole economy, do not use today the same energy sources as yesterday. How could economic models report on various historical situations, if those situations are contingent to material differences that are not caught by the models? Considering materiality would imply a renunciation to the discovering of atemporal principles – a path that many economists would not accept to take. This shortcoming is another consequence of the Newtonian tropism underlined by Georgescu-Roegen and Mirowski. The Newtonian laws are conceived as universal and atemporal laws. Since the neoclassical theory of production is based on such a mechanistic framework, it also leads to so-called universal and atemporal principles. Thus moving material forms cannot be taken into consideration.

Despite their reluctance to make space to the materiality of energy resources in their analyses, most economists have not totally ignored the role of energy resources in production processes. Yet their attitude towards materiality had consequences on the analytical role that they gave to energy. Are energy resources a factor of production, like labor, land or capital? Or are they a mere input, like raw materials? Energy has never found a stable place in the economics of production. I suggest that it is because its material specifications have not been taken seriously.

To illustrate this point, a short journey in the history of economic thought may be useful. In the 1890s and 1900s, the Austrian tradition, starting with Eugen Böhm-Bawerk (1884; 1889a; 1889b), proposed to redefine capital as a "roundabout way". This conceptual innovation raised controversies, opening a dialogue with Anglo-saxon authors like John-Bates Clark (1888; 1899), Philip H. Wicksteed (1894; 1910) and Irving Fisher (1896; 1897a; 1897b; 1904; 1906). Without comprehensively reporting on these controversies, it is noteworthy that these economists have felt some discomfort with energy resources. Böhm-Bawerk (1884, p. 224) highlights the exhaustible characteristic of fossil fuels, in particular coal, which tends to place energy as a peculiar factor of production, less immutable than land for example. He considers all natural forces (including energy) and materials as part of a global category "land", considered as a factor of production:

> Since all, or at least almost all, limited gifts and energies of nature are connected with land, we may, without much danger, take Land, with its activities or uses, as the representative of this economic natural endowment. (Böhm-

Bawerk, 1889a, p. 80)

Wicksteed (1910, p. 7) indicates that the services of nature, as part of land, are a factor of production. They can be replaced by labor or capital, as far as distribution is concerned. Further on (1910, p. 359-361), he changes his mind, looking at some specific natural resources, for instance ore, and he merely considers them as an input that disappears during the economic process, like raw materials. Accordingly, it should not be a subject for the economist, but only for the entrepreneur's accounting. Clark's position is somehow different, but even more ambiguous. In his view, energy resources, in particular fossil fuel resources, are a way of spending capital, defined as a factor of production, but they are a peculiar way of spending capital because they lead to an incorporation of this capital into the products, a characteristic that is usually hold by inputs. Here one might rightly be confused:

> The pure fund of capital may even stay longer in some kinds of passive capital-goods than it does in some active instruments. [...] Coal, too, is an active instrument: it is not in the mill for the purpose of receiving any additional utility, but is there for the purpose of helping workmen to impart utility. It transmutes itself into power, and saves muscle; but it perishes quickly. [...] Capital may stay for an instant in steam, and for an hour in the fuel that generates it, but it also stays for weeks in unfinished products. (Clark, 1899, p. 148n)

To a certain extent, Clark incorporates some materiality (perishability) in his reasoning, but it brings confusion in his own input-factor conceptual framework. In his extensive definition of capital, viewed as a stock of wealth, Fisher does not precisely know where energy resources should be placed. First (1896, p. 516, 533), he considers fuels as an income, like food, and therefore defines them as a flow of wealth, which looks like an input. Then (1906, p. 7), he categorizes fossil fuel resources in his conceptual batch "commodities/raw materials", as part of a stock of wealth, that is to say, according to his own definition, of a capital. It would be unfair to expound this semantic vagueness without admitting that Fisher's main distinction is between stock and flow, and that energy resources are both, according to the situation (ore stock in a mine or ore flow feeding a furnace). But it remains interesting to see that during this historical period of conceptual redefinition, there has been no stabilized place for energy resources, but many ambiguities in author's works with regard to the status of these resources in the economics of production.

This journey in the history of economic thought might be continued with another episode, when Robert M. Solow (1974a; 1974b) and Joseph E. Stiglitz (1974a;

1974b; 1976) impulsed a renewal in environmental macroeconomics. Solow's and Stiglitz's articles were published a few months after the oil shock and they were supposed to give answers to the criticisms addressed to dynamic economic models ignoring the Earth limits, as raised in the *Limits to Growth* report. Still under the Newtonian tropism, Solow and Stiglitz elaborate integrated models with aggregate variables, adding a natural resources factor (R) in the global production function. This addendum does not correspond to a rehabilitation of Ricardian land as a factor of production, but to an extensive vision of the resources and services that nature offers, including first of all exhaustible resources and fossil fuels. What about the materiality of these resources? And what about the status of energy resources in the economics of production? In his "The Economics of Resources and the Resources of Economics", Solow (1974b) uses material specifications in his definition of natural resources – he talks about "oil vein", "iron deposit", "recyclable materials" (p. 2) and "synthetic crude oil from coal" (p. 5). But as soon as he builds his formalized model (1974a), he puts aside these specifications and simply deals with natural (exhaustible) resources (R). In the production function, natural resources (R) are placed just next to capital (K) and labor (L), considered as factors of production. Does it mean that energy resources and raw materials become a factor of production, rather than an input-flow in the entrepreneur's costs? There is no precise answer, and that testifies of persistent ambiguities. Stiglitz (1976, p. 655) only tackles the word "energy", whereas Solow avoids it in his own analysis, speaking of "energy" only to hint at William Nordhaus' "The Allocation of Energy Resources", published in 1973. This latter paper is noteworthy because it directly refers to energy resources, and it seems to take into account some materiality (dissipation of energy, enumeration of different sources and different kinds of uses). However, Nordhaus' boldness has only last for a few years, before he came back to more integrated models in his further works (see Pottier, 2014, chp. 2). Would an extension of his 1973 study have led to a better understanding of energy resources in the economics of production? Perhaps, but it remains conjectures.

The conceptual instability of energy in standard economic theory is probably due to an insufficient comprehension of materiality. When energy consists of wood or fossils fuels, it is seen as a stock that can be stored in a warehouse, next to machines and tools. Economists therefore treat energy as a factor of production, like machines and tools. When energy consists of electricity from the grid, it is seen as an instantaneous flow that cannot be stored and that just enters production. In that case, economists consider energy merely as an input-flow. Because no clear distinction is made between wood, fossil fuels and electricity from the grid, in

particular in regard of their material specifications, the economic discourse about energy resources remains undecided. In fact, all these energy sources should be considered as input-flows, since they disappear during the production process. But, since input-flows are not strictly represented in the production function, that would mean that energy would be out of production models, which has no sense with regard to its importance in economic activities. Georgescu-Roegen was aware of this shortcoming, and he proposed his own materially-determined model to build new foundations for the economics of production.

2 Some attempts to incorporate materiality

As mentioned, materiality implies two main issues for economic analysis: heterogeneity and contingency. Both are linked with the qualitative characteristics of items, the former in statics, and the latter in dynamics. Apart from empirical models that describe the circulation of material flows in economic systems[2], one may find in the history of economic thought some theoretical attempts to take into account the qualitative dimensions and changes of the economic world. Two examples may be evoked: the von Neumann-Sraffa model, and Georgescu-Roegen fund-flow model.

The von Neumann-Sraffa model, synthesis of John von Neumann's (1945) and Piero Sraffa's (1960) proposals, consists of decomposing economic production in elementary processes, in order to qualitatively determine the role of time in economic activities (see Kurz and Salvadori, 2003). In this model, productive goods – *i.e.* capital –, are specified according to their age. In other words, two identical machines bought at different times, more or less used in past processes, are considered as different machines. As a result, each elementary process delivers a joint-product: a final output, and worn-out machines. The von Neumann-Sraffa model incorporates some materiality through its reporting on the qualitative changes of productive goods. Nevertheless, it remains almost silent with regard to energy resources. Concerning materiality as a whole, dynamic contingency is partly included but static heterogeneity is highly ignored: fixed capital (stock of machines) is transformed in circulating-capital flows (new machines as input-flows, worn-out machines as output-flows), and nothing is left for distinguishing between durable machines and raw materials or intermediate goods. In summary, in the von Neumann-Sraffa model, taking into account dynamic contingency (wear) leads to reject the static heterogeneity of inputs and factors of production (flow, stock, perishability or not, etc.).

At first sight, Georgescu-Roegen's fund-flow model is much more accurate in

[2]See for instance input-output analysis.

dealing with materiality. In the 1960s and 1970s, when he proposed his framework, Georgescu-Roegen wanted to get rid from two drawbacks of standard reasoning: the negligence of the material characteristics of items, and the ignorance of time in terms of qualitative changes. In other words, he challenged economic analysis both on static heterogeneity and on dynamic contingency. His fund-flow model, whose first intuitions were presented in 1965, consists of decomposing production in elementary processes, as von Neumann and Sraffa did, by adding a distinction between two kinds of productive agents: funds and flows. While funds pass through processes without deterioration, flows are either input-flows (raw materials, intermediate goods) or output-flows (products, waste), but never both (for details, see Maneschi and Zamagni, 1997, p. 701; Vittucci Marzetti, 2013, p. 210). Even though funds look like fixed capital (Kurz and Salvadori, 2003, p. 494), they are not stocks, as Georgescu-Roegen indicates, because they cannot be instantaneously accumulated:

> The difference between the concept of stock and that of fund should be carefully marked [...]. If the count shows that a box contains twenty candies, we can make twenty youngsters happy now or tomorrow, or some today and others tomorrow, and so on. But if an engineer tells us that one hotel room will probably last one thousand days more, we cannot make one thousand roomless tourists happy *now*. We can only make one happy today, a second tomorrow, and so on, until the room collapses. Take also the case of an electric bulb which lasts five hundred hours. We cannot use it to light five hundred rooms for an hour *now*. The use of a fund (*i.e.*, its "decumulation") requires a duration. (Georgescu-Roegen, 1971, p. 226)

This duration dimension of processes is at the core of Georgescu-Roegen's model. His idea is to formalize production as sequences of elementary processes that consist of the combination of funds (delivering productive services), and flows (both to create products and to maintain funds) inside temporal and spatial analytical boundaries. With land (L), capital (K) and labor (H) as funds; natural resources (R), inputs for production (I), and inputs for "maintaining capital equipment intact" (M) as input-flows; and products (Q) and waste (W) as output-flows, Georgescu-Roegen (1971, p. 231-232) formalizes an elementary process in the following way – [0,T] being the analytical boundaries, t the moment funds and flows combine each other:

$$[R(t), I(t), M(t), Q(t), W(t); L(t), K(t), H(t)]_0^T$$

The boundaries guarantee the contingency of the economic model, and the distinction between funds and flows offers heterogenous vision of productive agents. As a

result, materiality seems to fit into the fund-flow model. The production function is no more manipulable, the replacement of natural resources by machines becomes impossible, because funds and flows are not substitutable (see Daly, 2013, p. 22-23; Morroni, 2014, p. 6).

Georgescu-Roegen's reference to materiality in economic theory is however not comprehensive. Some commentators (see Kurz and Salvadori, 2003; Maneschi and Zamagni, 1997; Vittucci Marzetti, 2013) have noticed that the fund-flow model does not correctly report on worn-out machines and laborers' tiredness. This is a limit to Georgescu-Roegen's awareness about material changes. In fact, he avoids this issue, assuming (1971, p. 232) a "maintaining capital equipment intact" input-flow in his model. But as Kurz and Salvadori (2003, p. 492) underline, it is highly doubtful that this assumption is technically feasible, if not economically viable.

What about energy resources? Unlike standard economic theory, there is no ambiguity in Georgescu-Roegen's schedule. Energy resources are *flows*, entering the processes, and partially outgoing as high-entropy degraded energy (Georgescu-Roegen, 1971, p. 231-232). With his fund-flow model, he overcomes the indeterminacy of standard reasoning. While production takes place, energy resources disappear in their usable form. Therefore they can only be flows. But unlike what is at stake in standard reasoning, in which inputs (raw materials, intermediate goods) are ignored in the theory of production, such flows remain analytically crucial in the roegenian model – good point for the incorporation of materiality in the economics of production. As regards materiality, Georgescu-Roegen's fund-flow model might be attractive. But is it suitable for all energy regimes? To recall, materiality implies historical contingency. Although the analytical boundaries of the roegenian model guarantee the material specification of items and resources inside elementary processes, is it sure that all energy sources are flows? Renewables, with their own material characteristics, could challenge both the standard and the fund-flow models.

3 What about renewables?

Renewable energies, in particular potentially decentralized sources (wind, solar energy), have material specifications that differ from the materiality of fossil fuels: they are not stocks, since they cannot be stored in a warehouse, waiting for their use; they are neither mere input- or output-flows, since they do not (dis)appear during the process. What are they? They are a kind of constant or durable flow, keeping existing from the beginning to the end of the production process, but with

variable intensity. In standard reasoning, the durable feature of such a flow might bring these energy resources closer to a factor of production (as capital and labor) than to an input. But, as their time-irregularity implies, they are a peculiar factor of production assuming non-constant (and partially stochastic) returns, which would be hardly formalized in the production function[3]. Moreover, while capital requires maintenance and amortization, and labor demands rest and food, renewable energies need no human intervention to reconstitute themselves. Once more, standard theorists would be puzzled by such material characteristics.

A way of escaping these difficulties would be to consider, with legitimacy, that renewables are not available flows but services provided through capture machines (windmills, solar panels). As capital provides productive services, and labor offers human work, capture machines would provide renewable energy services. This might be accurate. Energy resources would however be rejected from the economics of production, because solely capture machines would be taken into consideration, within capital as a factor of production. It would be the same situation as in the previous examples (Böhm-Bawerk-Clark-Fisher and Solow-Stiglitz): energy would have an ambiguous role. Unsurprisingly, renewables do not solve the economists' discomfort with materiality.

As regards Georgescu-Roegen's model, renewables are not easily determined in the fund-flow distinction. Because they are not only input-flows disappearing during the production process, these energy sources are not exactly flows, as wood and fossil fuels were. On the other hand, even though there is some stability in their existence, the potential variability of their returns questions their fund status, which would require a constant efficiency according to Georgescu-Roegen's assumptions. As mentioned, renewables could be considered merely as services. In Georgescu-Roegen's schedule, they would come from a new kind of fund, for instance the biosphere. Such a position would challenge the role of natural resources as flows; but Georgescu-Roegen would probably have accepted such a shift for natural resources, since he defended (1971, p. 225) that the fund-flow status of economic items might change overtime.

Another way of including renewables in the fund-flow model is to be found in Katherine N. Farrell's and Kozo Mayumi's proposal (2009) to expand the roegenian conceptual nomenclature with a new item, namely meta-funds:

"Where a fund is a stock that enters and leaves an economic process (virtually)

[3]At a macro level, renewables might complete each other, and produce constant energy flows. Their durable dimension – the fact that energy flows no longer disappear during the production process – still remains a novelty.

> unchanged (providing only service), while a flow is consumed or qualitatively changed during the time it spends within an economic process (providing materials), a meta-fund is a special kind of fund where *service is provided from outside the defined boundaries of a specified production process*. Examples of meta-funds include human consciousness; social institutions; customs and traditions; the earth's sun; a fishery." (Farrell and Mayumi, 2009, p. 304)

Accordingly, as the authors themselves hint at, solar power (and other renewables) could be considered as meta-funds delivering renewable energy services from outside the process boundaries, and other natural resources would keep their flow status inside the production process. Perhaps it would be an accurate solution to amend Georgescu-Roegen's proposal with regard to the next energy transition. Placing renewables outside the process boundaries would nevertheless challenge the historical contingency dimension of the fund-flow model, which was supposed to be defined by the boundaries: is the historical contingency of renewables still observed if these energies are placed outside the boundaries?

Whatever the amendments standard and roegenian models may require, it is noteworthy that renewables, embodying new material characteristics, challenge the theory of production in its various forms. Even if Georgescu-Roegen's fund-flow model seems more plastic than the standard production function with regard to materiality, updates are also required.

Conclusion

Examining the economist's discomfort with materiality leads to several questions. Through heterogeneity and contingency, materiality challenges the conceptual architecture of standard economics, built upon aggregate and stable categories and variables. Does it make sense to deal with "energy resources" or "natural resources" broadly speaking, since these resources may have many different material specifications? The history of economic thought consists of several examples about the economists' discomfort with materiality. At the turn of the 19th century, the capital controversy was supposed to reshape the theory of production. Natural resources, including energy, have thus been mentioned, often with ambiguities. They were sometimes presented as a factor of production, sometimes as inputs in the entrepreneur's accounting. In the 1970s, Solow's and Stiglitz's growth models with exhaustible resources addressed some materiality issues. But they chiefly ignored energy in its various and evolutive forms.

The need for disaggregation because of the heterogeneity of economic items is a

recurrent topic in the history of economic theory. The Cambridge capital controversy is part of the same set of theoretical questions. Materiality adds a naturalist and physical dimension to those debates. The Cambridge controversy rested upon concerns about the measurement of capital, which was only one factor of production among others. Materiality addresses all the factors and inputs of production. It is a more general subject. As for energy resources, their materiality determines economic behaviors and structures, which cannot be ignored by economists. The fact that electricity cannot be stored, for instance, partially explains why spot markets are much more important than futures market for electricity. In the same way, because gas and coal have not the same physical properties, they cannot be exchanged inside industrial plants. On both micro and macro levels, investments in specific technologies create path dependencies. Can an economic theory of production ignore such mechanisms? If it aims at providing accurate results in production modelling, probably not.

Basically, materiality raises the issue of the relationship between man and nature in social sciences. As Emilia Ferraro and Louise Reid (2013) emphasize, most social scientists are still the heirs of a Cartesian epistemology assuming a cut between mind and material affairs. Economists do not deviate from this rule, and that might partly explain why they are so puzzled with materiality. To correct this bias, considering the economic agent as a world-oriented *homo-faber*, as Ferraro and Reid suggest, rather than a mere psychological *homo-œconomicus*, could be a good starting point. Such a shift would help economic theorists admit that the transition to renewables will probably be more than a technological shock, rather a theoretical novelty.

References

Böhm-Bawerk, E. (1884). *Capital and Interest. A Critical History of Economical Theory*. MacMillan & Co., London & New York. English translation by W. Smart, 1890.

Böhm-Bawerk, E. (1889a). *The Positive Theory of Capital*. G.E. Stechert & Co., New York. English translation by W. Smart, 1891 [reprint 1930].

Böhm-Bawerk, E. (1889b). Une nouvelle théorie sur le capital. *Revue d'économie politique*, 3:97–124.

Callon, M. and Muniesa, F. (2003). Les marchés économiques comme dispositifs collectifs de calcul. *Réseaux*, (6):189–223.

Clark, J. B. (1888). Capital and Its Earnings. *Publications of the American Economic Association*, 3(2):9–69.

Clark, J. B. (1899). *The Distribution of Wealth. A Theory of Wages, Interest and Profits*. MacMillan, New York.

Daly, H. E. (2013). A Further Critique of Growth Economics. *Ecological Economics*, 88:20–24.

Eyckmans, J. and Tulkens, H. (2003). Simulating Coalitionally Stable Burden Sharing Agreements for the Climate Change Problem. *Resource and Energy Economics*, 25(4):299–327.

Farrell, K. N. and Mayumi, K. (2009). Time Horizons and Electricity Futures: An Application of Nicholas Georgescu-Roegen's General Theory of Economic Production. *Energy*, 34(3):301–307.

Ferraro, E. and Reid, L. (2013). On Sustainability and Materiality. Homo Faber, a New Approach. *Ecological Economics*, 96:125–131.

Fisher, I. (1896). What is Capital? *Economic Journal*, 6(24):509–534.

Fisher, I. (1897a). Senses of "Capital". *Economic Journal*, 7(26):199–213.

Fisher, I. (1897b). The Rôle of Capital in Economic Theory. *Economic Journal*, 7(28):511–537.

Fisher, I. (1904). Precedents for Defining Capital. *Quarterly Journal of Economics*, 18(3):386–408.

Fisher, I. (1906). *The Nature of Capital and Income*. MacMillan & Co., London & New York.

Georgescu-Roegen, N. (1965). The Institutionnal Aspects of Peasant Economics: A Historical and Analytical Review. In *Proceedings of the Agricultural Development Concil Seminar on Subsistence and Peasant Economies*, Honolulu.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge (MA). [ed. 1999].

Greif, A., Milgrom, P., and Weingast, B. R. (1994). Coordination, Commitment, and Enforcement: The Case of the Merchant Guild. *Journal of Political Economy*, 102(4):745–776.

Kurz, H. D. and Salvadori, N. (2003). Fund-Flow versus Flow-Flow in Production Theory: Reflections on Georgescu-Roegen's Contribution. *Journal of Economic Behavior & Organization*, 51(4):487–505.

Maneschi, A. and Zamagni, S. (1997). Nicholas Georgescu-Roegen, 1906-1994. *Economic Journal*, 107(442):695–707.

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens III, W. W. (1972). *The Limits to Growth, A Report for the Club of Rome's Project on the Predicament of Mankind*. Potomac Associates, London.

Mirowski, P. (1989). *More Hear than Light. Economics as Social Physics, Physics as Nature's Economics*. Cambridge University Press, Cambridge (UK).

Missemer, A. (2013). *Nicholas Georgescu-Roegen, pour une révolution bioéconomique*. ENS Éditions, Lyon.

Morroni, M. (2014). Production of Commodities by Means of Processes: The Flow-Fund Model, Input-Output Relations and the Cognitive Aspects of Production. *Structural Change and Economic Dynamics*, 29:5–18.

Nordhaus, W. D. (1973). The Allocation of Energy Resources. *Brookings Papers on Economic Activity*, 1973(3):529–576.

Pottier, A. (2014). *L'économie dans l'impasse climatique. Développement matériel, théorie immatérielle et utopie auto-stabilisatrice*. PhD thesis, EHESS. Under the supervision of Jean-Charles Hourcade.

Solow, R. M. (1974a). Intergenerational Equity and Exhaustible Resources. *Review of Economic Studies*, 41:29–45.

Solow, R. M. (1974b). The Economics of Resources or the Resources of Economics. *American Economic Review*, 64(2):1–14.

Sraffa, P. (1960). *Production of Commodities by Means of Commodities. Prelude to a Critique of Economic Theory.* Cambridge University Press, Cambridge (UK).

Stiglitz, J. E. (1974a). Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths. *Review of Economic Studies*, 41:123–137.

Stiglitz, J. E. (1974b). Growth with Exhaustible Natural Resources: The Competitive Economy. *Review of Economic Studies*, 41:139–152.

Stiglitz, J. E. (1976). Monopoly and the Rate of Extraction of Exhaustible Resources. *American Economic Review*, 66(4):655–661.

Vittucci Marzetti, G. (2013). The Fund-Flow Approach: A Critical Survey. *Journal of Economic Surveys*, 27(2):209–233.

von Neumann, J. (1945). A Model of General Economic Equilibrium. *Review of Economic Studies*, 13(1):1–9.

Wicksteed, P. H. (1894). *An Essay on the Co-Ordination of the Laws of Distribution.* MacMillan & Co., London.

Wicksteed, P. H. (1910). *The Common Sense of Political Economy. Including a Study of the Human Basis of Economic Law.* MacMillan & Co., London.