Università Cattolica del Sacro Cuore

CENTRO DI RICERCHE IN ANALISI ECONOMICA
E SVILUPPO ECONOMICO INTERNAZIONALE

Natural Resources and Technologies

Alberto Quadrio Curzio -
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Abstract

This Working Paper joint two previous article by the authors:

The economic theory of exhaustible natural resources, in "Enciclopedia degli Idrocarburi", vol. IV, Istituto della Enciclopedia Treccani, Roma, 2008, pp. 3-10;
Technological innovation, relative scarcity, investments, in "Enciclopedia degli Idrocarburi", vol. IV, Istituto della Enciclopedia Treccani, 2008, pp. 11-22[•].

In the first one (cap. 1-4), we consider the contribution of economic theory (partly through a reevaluation of history) in order both to interpret and predict events, and to identify economic policies; this happens especially when the world economy feels the significant constraints imposed by some natural resources and raw materials, partly due to the rapid growth of a number of developing countries, and when there is an urgent need to increase resources rapidly to ensure continuing availability.

Even if the problem of scarce resources (of which natural resources are the most obvious category) has been central to analysis for centuries, natural resource economics is contradictory. The main reason for this is that economic theory is out of step with prevailing economic conditions, as a consequence of the varying concern for a crucial phenomenon in the dynamics of economic systems: the opposition-coexistence of the *scarcity* of natural resources and the *producibility* of commodities.

Natural resource economics can be summarized by dividing it into three main lines of thought: the theory of producibility and scarcity developed by classical economists; the theory of general and natural scarcities developed by marginalists and neoclassicals; the theory of dynamics with and without natural scarcities developed by macroeconomists, structuralists and empirical stylizers.

Using this three-way subdivision, which is not clearly codified in

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[•] We would like to thank the Istituto della Enciclopedia Treccani for the permission to re-print here these articles.

economic theory, the basic features of each approach will be examined with special attention to its early exponents.
The historical starting point is the second half of the Eighteenth century, although we will ignore contributions such as those made by the Physiocrats who, during the same period, developed a theory of production based on the surplus generated by agriculture.

In the second one (cap. 5-6), we consider that the role of technological innovation for resources use and conservation is often measured by empirical indicators of intensity or efficiency which express the evolution of resource use in relation to variables such as population and GDP. The historical evolution of these indicators tends to indicate a process of decoupling – in other words, a decrease in the energy/emissions intensity of economic activity or an increase in the efficiency/productivity of resource use.
These empirical regularities have led to the proposition of stylized facts representing the relationships between resource-use efficiency and economic growth known as environmental Kuznets curves.
However, the economic interpretations of the innovation mechanisms underlying the progress suggested by efficiency indicators, nonetheless, remain open and complex at the very time when there is increasing demand for further substantial advances in resource-use efficiency. We will survey the empirical evidence on the medium- and long-term dynamics of these indicators and will discuss their significance. This will be followed by an analysis of the possible role played by economic factors (especially resource prices and markets) and institutional factors (especially climate policy) in triggering and supporting progress in the use efficiency of energy resources.

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PART I - **The economic theory of exhaustible natural resources**

1. Introduction

The contribution of economic theory (partly through a reevaluation of history) is important both to interpret and predict events, and to identify economic policies; this happens especially when the world economy feels the significant constraints imposed by some natural resources and raw materials, partly due to the rapid growth of a number of developing countries, and when there is an urgent need to increase resources rapidly to ensure continuing availability.

Even if the problem of scarce resources (of which natural resources are the most obvious category) has been central to analysis for centuries, natural resource economics is contradictory. The main reason for this is that economic theory is out of step with prevailing economic conditions, as a consequence of the varying concern for a crucial phenomenon in the dynamics of economic systems: the opposition-coexistence of the *scarcity* of natural resources and the *producibility* of commodities. This relationship is mediated by scientific and technological progress which, in the long run, has gradually reduced opposition and overcome scarcity until now.

Over the long term, the distinction between exhaustible and renewable natural resources has been weak, since all resources have been renewed and augmented through substitution processes. Scarcities have therefore always been relative rather than absolute.

Natural resource economics can be summarized by dividing it into three main lines of thought: the theory of producibility and scarcity developed by classical economists; the theory of general and natural scarcities developed by marginalists and neoclassicals; the theory of dynamics with and without natural scarcities developed by macroeconomists, structuralists and empirical stylizers.

Using this three-way subdivision, which is not clearly codified in economic theory, the basic features of each approach will be examined with special attention to its early exponents. The literature on these themes is extensive, but in our opinion, the central issue remains unchanged: determining the influence of natural resource scarcity on growth processes. The subject thus has a specific focus and does not aim to provide a full overview.

The historical starting point is the second half of the Eighteenth century, although we will ignore contributions such as those made by the Physiocrats who, during the same period, developed a theory of production based on the surplus generated by agriculture.

This reevaluation will also closely follow some earlier studies (Quadrio Curzio and Pellizzari, 1981; Quadrio Curzio, 1997 and 1998).

2. Producibility and scarcity: the classical dynamics

The years 1776 to 1871 saw the intellectual hegemony of the classical economists: Adam Smith, Thomas R. Malthus, David Ricardo and John Stuart Mill. Their theory contained a grand design in which lie some fundamental principles for future reflections on the dynamics with natural resources. To summarize:

The principle that the existence of a *net product* and its accumulation are necessary conditions for the growth of economic systems. The intensity and continuity of growth increases in line with progress which, in turn, depends on the ability, skill and good judgement of labour. So Smith (1776) insisted on man's creative capacity, on the *almost unlimited producibility* of goods and means of production.

The principle that there is a structural gap between population growth and the increase of food supply: as the former grows according to a geometrical progression, it increasingly diverges from the latter, which follows an arithmetical progression. Thus, Malthus (1798) introduced the *absolute scarcity* of natural agricultural resources, predicting a tragic end for the dynamics of economic systems and for humanity.

The principle that in the dynamics of economic systems, the ongoing constraints imposed by limited natural resources could slow down or even halt growth, leading to a stationary state, if technical progress was insufficiently intense. Thus, Ricardo (1817) introduced the *relative scarcity* of natural resources, exploited in order of decreasing quality and on which technical progress could operate by limiting the constraints imposed by scarcity itself. This key principle in Ricardian theory has four other corollary principles: *a*) the rent is that part of the net product which can be attributed to the natural resource by virtue of the "original and indestructible powers" which it brings to the production process. It emerges as soon as the scarcity of the resource begins to condition production, and increases in the dynamic process which accentuates the scarcity itself; *b*) the price of the product generated by the natural resource (or, with reference to the Ricardian context, the price of corn produced by the land) also varies depending on the degree of scarcity, causing resort to increasingly less productive resources or expensive means of producing the same resource. As a result, price levels also change with economic dynamics, increasing in line with scarcity; *c*) the rational use of scarce resources implies that they are used in order of decreasing quality and productivity. This leads to the principle of diminishing returns; *d*) there is a relationship of interdependence between raw materials and commodities.

The principle of the inevitability and desirability of the stationary state, since technical progress can only delay the moment at which the economy reaches this point. So, according to Mill (1848), a stationary state is not negative, but may represent an ideal balance, encouraging moral and social progress. No growth in the population or wealth should not be interpreted as no improvement. Considering the potential impact of quantitative growth on the Earth's beauty, Mill hopes that man will choose a stationary state before being forced to do so by the exhaustion of resources resulting from population growth. In conclusion, Ricardo came closest to the opposition-coexistence paradigm. By reassessing Malthus' extremism and limiting Smith's optimism, he could have ascribed the essence of the dynamic workings of economic systems to the scarcity-producibility paradigm by admitting a process of continuous growth, albeit with phases of stagnation. Unfortunately, he was unable to fully exploit the concept of relative scarcity contained in his theory; by underestimating technical progress, he ended up predicting the advent of the stationary state without growth.

This is classical theory (which is sketchy regarding many aspects but, nonetheless, magnificent) on the principles of creation of the social product; its distribution among wages, profits and rents; and its subdivision between consumption and investments, on which the growth of ‘the wealth of nations’ over time depends.

The contributions of later economists develop some aspects of this theory and abandon others which subsequent insights will see as being of extreme importance.

This discussion will be highly selective, making reference exclusively to those economists believed to be most innovative.

3. From natural to general scarcities: marginalists and neoclassicals

Marginalist theory, which dominated from 1871 to 1936, and neoclassical theory, which followed marginalist theory, are based on the pairing exchange-scarcity: given the scarcity of resources and individual preferences, all economic problems are resolved through the efficient use of these resources and exchange between the individuals who own them.

Despite differences between the economists belonging to these two schools of thought and the necessity to oversimplify, we believe that they shared a general theory of stationary scarcity covering all production factors: land, labour and capital.

This explains why problems relating to natural resources lose their specific identity, becoming particular instances of a general theory of scarcity and marginal productivity. It also explains the pivotal importance of studying the conditions which allow for the optimal use of resources (and not only natural resources) which constrain production and consumption in a stationary context. In a situation where all production factors are scarce, the role of land in the process of accumulation and of natural resources in processes of growth, does not require specific analysis. Nevertheless, even within this line of thought, there are some specific studies of natural resources, although these are not considered sufficiently important to form the basis for a general theory.

3.1. Energy resources, intensive-extensive use, limitations on development

The first contribution of note is by William Stanley Jevons (1865), also considered a forerunner of marginalism. He predicted the end of British industrial supremacy due to the rapid exploitation and progressive depletion of mines, leading to a loss of competitiveness and development compared to other countries, richer in natural resources. Jevons believed that an increase in the energy efficiency of coal use could not prevent stagnation, since this would not lead to more preservation but to an increase in the scale of production and, thus, more consumption. Essentially, technical progress would lead to a less intensive use of coal which would be more than offset by its more extensive use. Jevons thus underestimated the potential of technical progress to identify and develop alternative energy sources, but his pioneering work highlighted a problem which is still important, concerning the constraints placed on a country's development by the availability of energy resources.

3.2. Use of natural resources and social well-being

The second contribution, considered the foundation for all subsequent theories, is that of Harold Hotelling (1931). In his famous article, Hotelling attempts to define the rate of depletion allowing the owner of an exhaustible resource to maximize obtainable profits.

Since the resource stock is limited, an increase in current depletion entails a reduction in future depletion; to maximize profits, under conditions of perfect competition, the present value of the revenue of the resource in any given period, net of extraction costs, must be the same; otherwise it would be possible to increase profits by changing depletion in different periods. If extraction costs are negligible, the resource must be depleted so as to allow the price to grow in line with interest rates. With this result, known as *Hotelling's rule*, the ownership of an exhaustible resource is equivalent to the ownership of any other financial activity.

Hotelling shows that competitive depletion is also socially optimal: the depletion rate of a mine which maximizes obtainable profits also allows for the maximization of the resource's social value, whereas a monopoly leads to a lower rate of depletion than that which would be socially desirable. However, it is important to underline that Hotelling demonstrated the efficiency of the depletion rate under competitive conditions, defining social well-being in terms of resource consumption and discounting the benefits deriving from future consumption; this procedure could be heavily criticized for the different importance attributed to different generations.

3.3. Non-renewable resources: constraints on growth and technical progress

Hotelling's work influenced an enormous quantity of literature, especially during the 1970s, when the energy crisis became manifest in all its severity. Within this literature, which can be traced back to neoclassical aggregate growth models, two different lines of thought can be identified: one concerning renewable resources and the other concerning non-renewable resources. Both renewable and non-renewable resources can be depleted; the former can be regenerated and thus decrease, increase or remain constant depending on the interactions between depletion and natural regeneration capacity; the latter are finite and the artificial regeneration process, or recycling, where possible, is conditioned by costs and technology.

Below, this discussion will be limited to contributions concerning non-renewable resources. Since it is impossible to describe each individual study, their most important features will be summarized. Often fairly complex in formal terms, these contributions are similar for the techniques used, mainly the theory of optimal control, and the issues tackled. These concern both the problem of how best to deplete resources in accordance with the constraints imposed by the resource stock, the size of the work force and available technology, and the problem of ascertaining if limited availability may constrain potential growth.

Since the continuous depletion of non-renewable resources inevitably leads to exhaustion, it becomes important to predict if economic activity is sustainable and whether a given level of *per capita* consumption can be maintained (Stiglitz, 1974). Non-renewable resources are a constraint when they are essential to production; however, this constraint may be mitigated by technical progress, which can lead to both lower consumption of the exhaustible resource and the potential for recycling, by lengthening the depletion period of the exhaustible resource. Above all, however, technical progress can allow for the substitution of these resources with others available now or in the future.

Technical progress is thus crucial in order to counter the constraints imposed by non-renewable resources and studying the factors that encourage technological advances becomes fundamental. Although some works suggest that technical progress is exogenous, does not entail costs and proceeds steadily, in more realistic studies, technical progress depends on a series of decisions (research, investment, etc) which cannot be considered exogenous.

However, despite the inevitable uncertainties regarding technology's role in freeing us from the constraints imposed by non-renewable resources, many studies are characterized by an optimistic view of man's inventive capacity. They thus aim to develop rules for non-renewable resource management, so as to ensure that the decrease in stock is offset by an increase in investments in human capital, and to ensure the maintenance of a given level of production and consumption.

3.4. Non-renewable resources and optimal depletion

The optimal depletion of non-renewable resources can be defined in terms of both social and private goals.

Socially optimal depletion must create the most socially desirable situation, and therefore requires the definition of those factors which influence social well-being. In such analyses, the most important problem derives from the fact that the term 'social well-being' is heavily debated. Social well-being depends on the availability of goods and services, but also on their distribution. Thus, evaluating social well-being involves a value judgement on the optimal distribution, both within a given generation and among different generations, posing the additional problem of what time interval to consider.

Two specific concepts of well-being have frequently been adopted in the literature on social optimal exploitation. The utilitarian approach (Dasgupta and Heal, 1974) states that social well-being is maximum when the sum of the utilities due to consumption by different generations is maximum. The utility of future generations is thus discounted, a practice justified by some on the basis of uncertainty but heavily criticized by others for the different importance attached to different generations. The egalitarian approach (Solow, 1974b) is inspired by the rules of distributive justice upheld by John Rawls (1971), according to which the optimal path must equalize the well-being of different generations at the highest possible level. If social well-being is determined on the basis of *per capita* consumption, well-being can be maximum only if *per capita* consumption is maximum and constant over time. These different concepts of social well-being have had a crucial influence on the definition of the optimal depletion policy.

Studies aimed at determining the optimal depletion path for resource owners generally have as their objective the maximization of the profits obtainable from depletion. Since the depletion rate thus determined may differ from that which is socially desirable, analyses have been undertaken on the policies to be adopted in order to eliminate divergences and allow for resource depletion which is compatible with the maximization of social well-being.

The determination of the optimal depletion rate from a private point of view also poses the problem of the best time-span to consider for the resource owner, despite the absence of the problems of distributive justice mentioned above. Since obtainable profits depend on the relationship between the price of the resource and depletion costs, this literature investigates the factors which influence these variables. In particular, attempts are made to: *a*) determine the depletion path and the price dynamics, with reference to different market regimes; *b*) analyse the changes in the optimal path, considering the potential substitution of the exhaustible resource with other resources, both exhaustible and renewable; *c*) analyse the potential for recycling and its costs; *d*) analyse the effect of changes in variations in extraction techniques, in the costs of depletion, in the prices of potential substitutes, in the estimates of reserves, in the rate of interest and in demographic dynamics. The variety of approaches makes it impossible to present a detailed analysis here, although it is worth considering some results referring to specific hypotheses, showing the conditions which are necessary along an optimal depletion path.

3.5. Exploitation of non-renewable resources. Price and royalty dynamics: a simplified model

A non-renewable resource differs from a normal commodity in that it is non-producible and is available in limited quantities. Current depletion thus has an opportunity cost, given by the benefit of using the resource in the future rather than at the present. This opportunity cost, also known as the royalty, must be taken into consideration in depletion decisions. It accounts for the difference between the normal requirement of efficiency in the use of producible resources (which implies that the price and the marginal extraction cost are identical) and in the use of exhaustible resources (whose price must be higher than the marginal extraction cost and thus equal to the depletion cost, plus the opportunity cost).

A further condition for efficiency in the depletion of exhaustible resources concerns variations in royalty and price over time. If the depletion costs are negligible, the price of a unit of extracted, or surface, resource is equal to the price of a unit of resource in the ground, in other words to the royalty; as already shown by Hotelling, both must grow in line with interest rates. Even if the resource owner decides not to deplete it, he thus has an income because the value of the non-extracted resource grows at the rate of interest.

When the marginal extraction cost is constant, the royalty grows at the rate of interest; since the price is equal to the sum of the royalty and the marginal extraction cost, its trends will depend on the weight of these two components. If the value of the royalty is initially low, that is the amount of available resource is high, the price of the resource (which is dependent on the marginal extraction cost, assumed to be constant) grows more slowly than the interest rate; the fact that the resource is exhaustible thus has a minimal impact. As time passes, however, since the royalty grows at the rate of interest, its impact on the surface price of the resource increases and the price thus tends to increase until its growth rate equals the interest rate. However, there is a limit on price increases which depends on the maximum marginal willingness to pay for the exhaustible resource: in many studies, this limit is represented by the price of a substitute. In the simplest models, optimal depletion must involve price increases so as to cancel out demand at the exact moment when the resource is exhausted, simply stating the end of the era of that resource (Solow, 1974a). If there are substitutes which are not currently competitive, optimal depletion must entail price increases to allow for the use of other previously unused resources, and the resource must be exhausted at the point when it becomes economically viable to use the substitute. If there are no current substitutes, optimal depletion must entail price increases to encourage both a greater efficiency in the use of the resource and greater investments in the search for alternative resources.

3.6. Non-renewable resources: scarcity and efficiency

The analytical scheme described above has been used to investigate how depletion paths should be modified. It considers that the depletion of exhaustible resources begins with the best and most easily accessible reserves, with effects on the dynamics of extraction costs; knowledge of the resource stock is limited, but can be improved by exploration and research activities.

Further alterations in important parameters and functions have been introduced in later models in order to improve the analysis of non-renewable resource depletion and make it more realistic. However, despite these innovations, contributions to this line of research seem directed more at analysing the problems posed by the scarcity of natural resources in terms of efficiency than in terms of constraints on growth.

4. Dynamics with and without natural scarcities: macroeconomists, structuralists, stylizers

Since economic theory never develops in a linear fashion, a single problem often attracts opposing, compatible or complementary theories. Thus, during the 1940s, while the neoclassicals continued their analysis, theories based on classical economics emerged successfully to tackle the dynamic phenomena of economic systems. The interest in this field had never completely disappeared, as demonstrated by Joseph Alois Schumpeter who developed a dynamic theory in 1911, which was elaborated upon during subsequent decades. However, it was probably the study by John Maynard Keynes (1936) which brought to the fore a macroeconomic approach based on the classicals (Pasinetti, 1977). It also became apparent during these years that technical progress had been continuous in the economies of industrialized countries for over a century, with increases in production capacity through accumulation. Below, we will examine some exponents of this approach, subdividing them into macroeconomists, optimistic structuralists and realistic structuralists, and empirical stylizers.

4.1. Macroeconomists

Roy Forbes Harrod (1939 and 1948) examines the accumulation of capital, the dynamics of the work force and technical progress. As far as natural resources and land are concerned, after essentially restating classical theory, Harrod accepts the theory of a driving force due to accumulation, but criticizes it for various aspects and abandons two: population dynamics, which for Harrod become exogenous; the dynamics of diminishing returns from land, which he considers quantitatively negligible so that he does not attribute a role to natural resources in his dynamic theory.

In the neoclassical macrodynamic mould, Robert Solow (1956) assumes that there are no scarce resources which cannot be augmented, stating that the introduction of a scarce earth factor would obviously lead to Ricardian diminishing returns. Essentially, these reformulations of dynamic theory underestimate scarce resources, as it is evident also in important reviews of growth theories (Hahn and Matthews, 1965).

4.2. Optimistic structuralists

Optimistic structuralists develop multisectoral models. The first in chronological order, in 1937, is John von Neumann (1945-1946), who tackles the problem of maximum growth; albeit with numerous significant differences, he also lays the foundations for the approach based on industrial interdependencies adopted by Wassily Leontief (1941 and 1953). Other economists proceed along the same lines, including Luigi Lodovico Pasinetti (1965 and 1981).

For von Neumann, goods are products not only by natural production factors but, above all, by themselves. This means that natural production factors, including labour, do not pose problems for growth. The limitations on scale imposed by natural production factors is thus denied, although their role in production is recognized. Leontief is more cautious, although whilst considering all sectors which treat raw materials in his theoretical and empirical work, he does not examine the limitations of scale imposed by natural resources on the production system. In this context, he writes: "Invisible in all these tables, but ever present as […] a whole additional set of factors determining this country's [the USA's] productive capacity and, in particular, its comparative advantage vis-à-vis the rest of the world, are the natural resources […] Absence of systematic quantitative information, similar to that which has been collected […] with respect to capital and labour, prevents us as yet from introducing this important element explicitly into this preliminary analysis" (Leontief, 1953, p. 96).

Pasinetti is another economist who has developed multisectoral models, but without considering natural resources and the constraints which these place on dynamics. However, he does consider accumulation, technical progress, the distribution of income and human capital.

These structural theories represent extremely important contributions to an understanding of dynamics, technologies, technical progress and accumulation. However, they lie at the opposite extreme to the marginalist approach, moving from generalized static scarcity to absolute dynamic producibility and ignoring relative dynamic scarcity, in which natural resources matter. The return to the classicals is thus more Smithian than Ricardian. Of the pairing scarcity-producibility, more importance is attributed to the latter in the often implicit belief that technical progress and the rapid growth of industrialized economies eliminates the constraints imposed by resources. These authors are therefore fundamentally optimistic.

4.3. Realistic structuralists

A structural theory which espouses the role of land and raw materials is that of Piero Sraffa (1960), developed as early as the 1930s. This theory deals mainly with the relationships between the distribution of income (salaries, profits, rents), the prices of commodities and raw materials, and the choice of production techniques in a one-period context.

This theory, described as neo-Ricardian by some, devotes little space to natural resources, but borrows some important categories from the classicals. This leads to subsequent theories including natural resources which, for dynamic analysis, have also made use of variations on multisectoral models like those developed by von Neumann and Leonfief. We refer in particular to the approach adopted by Alberto Quadrio Curzio (1967) and taken up in studies by other authors (for a review: Quadrio Curzio *et al.*, 1996; Quadrio Curzio, 1997), including those by Quadrio Curzio and Fausta Pellizzari (1981 and 1996) which includes all the previous contributions, also dealing with many other problems. These works are about natural resources and raw materials in multisectoral production theories, both one-period and dynamic. Two sets of production sectors are considered, with analytical simplifications: in the first set, each specific sector produces a single commodity with the use of commodities and produced means of production; the second set comprises sectors which also make use of non-produced means of production, i.e. natural resources (such as land) and which generate raw materials (such as corn), also used as means of production in the first set of sectors.

These studies do not consider the isolated instance of a single natural resource, but rather the productive interdependence of the whole economy, prices and the distribution of income. As such, the theory has four central categories.

Natural resources and raw materials. The most obvious distinction is between reproducible and non-reproducible resources, not always crucial considering the long-term substitutability linked to technical progress. In other words, not everything comes down to the distinction between land and agricultural raw materials (renewable) on the one hand, and mineral deposits (exhaustible) on the other.

In a one-period context, the difference between reproducibility and non-reproducibility loses significance. A mineral deposit, measured in terms of volume or surface units per unit of raw material produced, has the same impact on production as land does on corn. Furthermore, several deposits are usually in production given the limited extraction capacity of each, per given time unit, compared to the level of production required. This is the case for lands of differing quality.

In a dynamic long-term context, all natural resources are historically reproducible, since scientific and technical progress has always moved the constraints imposed by scarcity forwards, albeit with slow growth and complex substitution mechanisms. For this reason, the distinction between reproducible and non-reproducible resources in the long term is not, historically, crucial.

Intensive rents and extensive rents. Rents are coessential with natural resources and are part of the net national product which can be attributed to scarce resources. There are two types of well-known rents from scarce natural resources: intensive and extensive. Restricting this discussion to extensive rents, which may include intensive rents, these emerge when two or more natural resources of differing quality are in activity, each producing a homogeneous raw material.

The analysis of rents establishes two orders for scarce natural resources: the order of efficiency and the order of rentability. The first depends on costs per unit of product and on production per hectare, and is the one adopted in producing lands. The second explains how rents behave in already active processes, when the economic system's level of activity grows by increasing the number of land processes in operation.

Techniques and compound technologies. Techniques are characterized by a multiplicity of interdependent sectors, each using a natural resource and producing a raw material involved directly or indirectly in the production of all other commodities. Technologies, on the other hand, are *n* active techniques, since each has a maximum production scale restricted by the scarcity of the natural resource used.

This concept also leads to an analysis of how the technology is modified within the dynamics as a result of the existence of non-produced natural resources and means of production. On the basis of a compound technologies scheme, with a multiplicity of techniques each characterized by a non-produced natural resource or means of production, the *composition* of these techniques in processes of accumulation and growth is analysed. This involves a complex analysis of orders of efficiency (dynamic-physical, dynamic-values and dynamic prices-distribution) among techniques and thus their order of activation in accumulation and in the dynamics itself. This results in various dynamics which are non-proportional due to the different structure of technologies, depending on the size of production surpluses which cannot be accumulated.

Technical-technological progress. Technological scarcity is inversely related to technical progress. A complex series of technical progresses is identified (structural, natural, linear, absolute, relative) since in the compound technologies model, progress can only be classified through reference to numerous variables. The distinction between progress in a technique and in a technology makes it possible to evaluate the interrelationships between technical and technological progress. This distinction also makes it possible to determine the consequences of these progresses regarding the extent to which the economic system can accumulate and grow, and weaken the constraints imposed by non-produced means of production.

This structural analysis, whilst certainly schematic and incomplete, clearly shows elements of realism. It takes into account the constraints imposed by natural resource scarcity, as well as historical reality, in the classification of different types of technical progress. It should not be forgotten that historically, the constraints imposed by natural resources have always been overcome in the long term.

4.4. Empirical stylizers

This name covers a variety of different types of analysis which share stylized historical or quantitative methods, extremely important in reducing the gap between the abstractions of pure theory and the full description of phenomena. This has led to the construction of an extremely important semitheory which has produced some significant results and complements to pure theory.

The first line of research of interest here is the historical-quantitative study of growth and development, which gathered momentum in the 1930s with the fundamental contributions by Simon Kuznets (for a brief overview: Kuznets, 1990).

Kuznets believes that attention should again be focused on long-term dynamics, in the mould of the classical economists, and on century-long dynamics which contain shorter cycles. The historical-quantitative approach is extended by Kuznets, in his numerous later works, to other central issues in development such as: *a*) the relations between demographic trends and economic development; *b*) the influence of technological innovations; *c*) structural transformations; *d*) historical tendencies to inequalities in income; *e*) the accumulation of capital; and *f*) the limited international spread of development.

This historical-quantitative theory thus shows the complexity of development, dealing with natural resources and the environment when: examining the structural transformations of the economy and agriculture; examining the accumulation of capital; analysing technological innovations and their importance for energy and industrial activities; analysing the impact of innovations on the environment. In short, it can be said that Kuznets is optimistic regarding the ability of technologies to respond, through adaptation mechanisms, even to the negative effects on the environment which they may cause. The other line of analytical-quantitative thought worth mentioning here is Leontief's (1977), applied to natural resources. It should be remembered that his contribution has been included by some in the category of large global predictive models which originated in the 1970s. This pairing seems unconvincing, partly because whilst Leontief bases his work on economic theory, global models are non-theoretical predictions, and partly because Leontief, to some extent, reacts against those global models which make extremely pessimistic predictions about the exhaustion of natural resources and the fear that the world economy will collapse. These models support the concept of an absolute scarcity of natural resources, leading to proposals that a generic condition of ecological and economic stability should be attained, a sort of stationary state (Meadows *et al*., 1972). Leontief develops a model of the world economy based on the economic theory of input-output, reaching the conclusion that natural resources-raw materials determine a condition of relative scarcity. The model consists of various interconnected input-output submodels relating to different parts of the world, analysing the interrelationships between the production and consumption of goods and services, and that of natural resources. Leontief's conclusion is very similar to that of Kuznets, and can be summarized as follows: "the principal limits to sustained economic growth and rapid development are political, social and institutional in character rather than physical. No insurmountable physical barriers exist within the Twentieth century to the accelerated development of the developing regions " (Leontief *et al*., 1977, pp. 10-11).

A new interest in global modelling has emerged in parallel with environmental concerns when these have been perceived as dangers of a systemic global nature in recent years. Alongside the increasing production of global ecological models – especially those for climate, and large multidisciplinary models of the large-scale interactions between ecological and social systems – there has been a resumption of global modelling in the 1970s mould, or similar to it, mentioned but not dealt with in detail here.

In conclusion, we believe that there is a continuing opposition between approaches dealing with global constraints and absolute scarcity, and those dealing with relative scarcity. This divergence results from the different evaluations of the potential impact of innovation and its generation mechanisms, which still appears to be the element of major division between the two approaches, even in their most recent environmentally-oriented form.

PART II – **Technological innovation, relative scarcity, investments**

5. Innovation and resource use efficiency: stylized facts

The role of technological innovation for resources use and conservation is often measured by empirical indicators of intensity or efficiency which express the evolution of resource use in relation to variables such as population and GDP. The historical evolution of these indicators tends to indicate a process of decoupling – in other words, a decrease in the energy/emissions intensity of economic activity or an increase in the efficiency/productivity of resource use. These empirical regularities have led to the proposition of stylized facts representing the relationships between resource-use efficiency and economic growth known as environmental Kuznets curves (Stern, 2004), given their similarities with the regularities identified by Simon Kuznets (1955) in the long-term relationships between economic growth and the distribution of income.

The importance of these indicators lies also in the fact that some international and national institutions use them to evaluate the effectiveness of energy-environmental policies and sustainability strategies (IEA, 1997, 2001a,b; OECD, 2002; DEFRA/DTI, 2003; EEA, 2003).

Furthermore, some countries tend to set intensity/efficiency targets for important policies; an example is the target on emissions intensity in relation to GDP adopted by the United States in its own climate policy as an alternative to the Kyoto Protocol target based on emission levels.

However, the economic interpretations of the innovation mechanisms underlying the progress suggested by efficiency indicators, nonetheless, remain open and complex at the very time when there is increasing demand for further substantial advances in resource-use efficiency. This chapter will survey the empirical evidence on the medium- and long-term dynamics of these indicators and will discuss their significance. This will be followed by an analysis of the possible role played by economic factors (especially resource prices and markets) and institutional factors (especially climate policy) in triggering and supporting progress in the use efficiency of energy resources.

5.1. Decoupling indicators and environmental Kuznets curves: meaning and limitations

With reference to a scheme of type $I=P \cdot A \cdot T$,[1] the total impact (I, e.g. the consumption of energy) can be expressed as the product of the impacts of population P, affluence A, i.e. the level of development measured by *per capita* GDP, and of the impact per unit of economic activity, i.e. I/GDP, as an indicator of the system's technology, T. Thus formulated, this is an accounting identity, useful for the decomposition analysis of the relative role of P, A and T in the evolution of I over time or its differing levels in different countries.

The role of P and A as pressure factors (generally increasing) pushing I to increase is obvious, whereas T is an intensity indicator which measures how many 'impact units' are required by an economic system (or by a sector) to produce one unit (one euro) of GDP. It is therefore a technical coefficient which, if referred to the system, represents its overall efficiency in the use of a given resource and expresses the average state of technology in a highly stylized way. A decrease in T over time indicates an increase in efficiency, and may be considered a direct indicator of decoupling between economic activity and resource use.

IPAT-like schemes highlight three features of decoupling analysis and Kuznets curves. First, if the dynamics of T alone are examined, this may provide misleading indications of the crucial or even

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[1] Starting from Ehrlich's formulation (1971), numerous variants of this scheme have been used to study the dynamics of global resources, especially in relation to population.

exclusive role of technological innovation for resource-related problems. The decrease in *T* may be strong, but *I* may be stable or increasing if increasing efficiency is insufficient to offset the scale effect caused by the growth of *P* and *A*. The reverse may also occur in phases when poor economic growth (decrease in *A*) causes *I* to decrease, but not *T*, as was the case in Eastern Europe and Russia at the beginning of the 'transition to the market' in the 1990s. Therefore, a decrease in *I* is always a positive sign for resources, but it may not result from a structural improvement in the specific efficiency of resource use (i.e. in *T*); by contrast, a decrease in *T* always indicates a structural increase in efficiency, but does not necessarily mean that total resource use (i.e. *I*) is declining. The ambiguous implications of decreases in *T* are important, for example, in the case of global greenhouse gas emissions, where *T* is deceasing (efficiency is increasing) but *I* is increasing. This is important, for example, in appraising the United States climate policy, which sets a target for the emissions intensity of GDP, i.e. for *T*, in contrast to the emissions level target, i.e. for *I*, adopted by the Kyoto Protocol. In this case, even significant achievements on the *T*-based targets do not necessarily mean a successful policy in terms of *I*, which is the environmentally relevant variable.

Second, although a decrease in *T* indicates that something positive is occurring in the system, this must be explained in technological and economic terms. In the *IPAT* scheme outlined above, it is assumed that the variables *P*, *A* and *T* are independent of one another. In fact, the dynamics of economic systems show that these three variables are interdependent, due to a series of direct and indirect causal links and, over the medium to long term, to dynamic feedback mechanisms. For example, the evidence suggests that population dynamics (*P*) depend partly on the dynamics of *per capita* income (*A*) and, to some degree, vice versa[2]. Similar relationships and feedback mechanisms also emerge for *T*, whose dynamics may depend on GDP (*per capita*), and vice versa if *T* refers to a key

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[2] For a survey of the different viewpoints of economists on the positive or negative effect of population on economic growth: Zoboli, 1996.

resource such as energy. Furthermore, the dynamics of *I* may also influence that of *T* if the scarcity signalled by the impact stimulates, through the markets (relative prices) or policies, processes of invention, innovation and diffusion of new technologies, resulting in specific efficiency in the use of that resource. In practice, a decrease in *T* reflects a complex combination of economic and technological micro- and macro-processes, including dynamic feedback mechanisms, which are of a heterogeneous, non-deterministic and partially endogenous nature. These will be discussed in detail in the remainder of this analysis. Third, Environmental Kuznets Curves (EKC) concern precisely some of the relationships mentioned above, for example, between *I* and GDP or between *T* and GDP (*per capita*); however, though they may supply empirical regularities of great heuristic interest, they do not provide a satisfactory economic explanation for them. The hypothesis suggested by the EKC is, in short, that an inverted U relationship between resource consumption and *per capita* GDP can be documented for a certain number of resources, pollutants and energy sources. Consumption (of energy) or emissions (of pollutants) initially increase when levels of economic development are relatively low, since a scale effect, driven by *A* and *P*, prevails; they later tend to decrease more or less proportionally when levels of economic development are higher, becoming decoupled from *per capita* GDP due to the predominance of an efficiency effect driven by *T*[3]. Like its original Kuznetsian formulation for income distribution, this hypothesis is based not on a theoretical model but on an insight originating from, and supported by, empirical evidence. Only recently have some studies attempted to formulate the EKC hypothesis in formalized models (Andreoni and Levinson, 2001; Chimeli and Braden, 2005).

This discussion will not cover the theoretical formalization and different formulations of EKCs. It is worth noting, however, that if the formulation concerns a relationship between *I* and GDP (*per capita*), the analysis of EKCs supplies the same information as the

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[3] For a presentation of EKCs with a discussion of the main hypotheses and empirical evidence: De Bruyn *et al*., 1998. Detailed surveys of the literature are presented in: Dasgupta *et al*., 2002; Dinda, 2004; Stern, 2004.

analysis of *T*. Furthermore, if an EKC relationship between *I* and GDP (*per capita*) is hypothesized, there must also be one between *T* and GDP because *P* and GDP always increase (with some exceptions) in the medium-long term, and decoupling must therefore have occurred at some level of GDP. By contrast, if there is an EKC relationship between *T* and GDP (*per capita*), this does not necessarily mean that there is a similar relationship between *I* and GDP, since *P* and GDP may have driven *I* more than could be offset by the decrease in *T*. This is true, for example, for global CO_2 emissions (see below).

The main limitation is that by identifying GDP (*per capita*) alone as the principal explanatory variable, the analysis of EKCs suffers from the same limitations as the analysis of decoupling, or of *T*, but with an additional danger. The empirical evidence provided by EKC relationships might actually give the misleading impression that rapid growth towards high levels of *per capita* GDP automatically leads to efficient resource use, and that the best policy for reducing their environmental impact is economic growth. However, the *IPAT* scheme indicates that a growth in GDP (*per capita*) necessarily leads also to a scale effect on resource consumption and emissions for each level of *T* and *P*.

Generally speaking, only if the negative effects of the increase in GDP (*per capita*) on *T* are constantly higher than its positive effect on *I*, can the process of economic growth lead to an absolute decrease in *I*, assuming the effect of population growth as given[4].

This is important for global energy consumption and greenhouse gas emissions, given the rapid growth of population and income in developing countries. The negative elasticity of *T* on the growth of *per capita* GDP will need to be extremely high in the near future, due to a stationary or even increasing *T* in many of these countries, in order to avoid a possible ‘catastrophe of scale’ resulting from the dynamics of income and population. Therefore, although the

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[4] If $I=f(P, A, T)$, where A is an indicator of economic development, with $\partial I/\partial A$, $\partial I/\partial P$, $\partial I/\partial T>0$ and $T=g(A)$, with $dT/dA<0$, the total derivative of I on A will be negative if $\partial I/\partial A \bullet \partial I/\partial T dT/dA$, i.e. if the direct positive effect of A on I is less than the negative effect of A on T, given the effect of T on I.

relationship between economic growth and environmental efficiency is an important stylized fact, economic growth remains only an implicit explanation of environmental efficiency and does not obviate the need for explicit strategies to improve *T* through specific innovations.

5.2. Indicator trends and empirical analyses

Indicators of energy intensity/efficiency and of emissions from energy sources (i.e. *T* in the above scheme) have been monitored for years by various international bodies (such as the IEA, International Energy Agency), national agencies (such as the US Department of Energy, DOE) and other institutions. Despite a constantly increasing energy consumption, the emerging trends are towards an increasing energy intensity of GDP (primary sources) only in those developing countries with low development but rapid growth, and a constantly decreasing energy intensity of GDP in all other countries.

The consumption of primary energy per unit of GDP was already decreasing by the late Nineteenth century in the United Kingdom, and by the 1920s and 1930s in the United States, Germany and France. In Italy, delayed industrialization led the energy intensity of GDP to increase until the 1950s, although it remained structurally low in comparison to other countries, followed by decreasing intensity from then until the present. From the 1970s, coinciding with the oil shocks, these trends were further consolidated, spreading to all developed countries. In Germany, for example, real GDP increased by 50% between 1970 and the early 1990s, whereas the consumption of primary energy remained almost constant.

The decline in the energy intensities (primary sources) has recently involved numerous developing countries still in the initial phases of industrialization. In China, for example, despite an enormous increase in the demand for energy, the reforms in the late 1970s, aimed at raising energy prices, led the energy intensity of national income to decrease by 50% between 1980 and the late 1990s (Zhang, 2000).

Numerous studies have investigated the general and specific factors involved in the decrease of energy intensities over time. Generally speaking, decreases in individual developed countries can be ascribed to: changes in the sectorial mix of the production structure, especially the relatively decreasing weight of energy intensive sectors, partially reflecting changes in the division of labour between countries on a global scale; substitution between sources and changes in the energy mix, resulting in higher economic output at any given level of total energy consumption; specific technological innovations for energy conservation and efficiency.

The decline in the energy intensity of output has led to a parallel decrease in the intensity of CO_2 emissions in relation to GDP, magnified by the 'decarbonization' of energy consumption through a continuous transition towards sources with lower specific emissions. In the United States, the carbon intensity of primary energy consumption has fallen by 0.25% per year since 1800, whereas the corresponding decrease worldwide has been 0.3% from 1850 (Gruebler *et al.*, 1999).

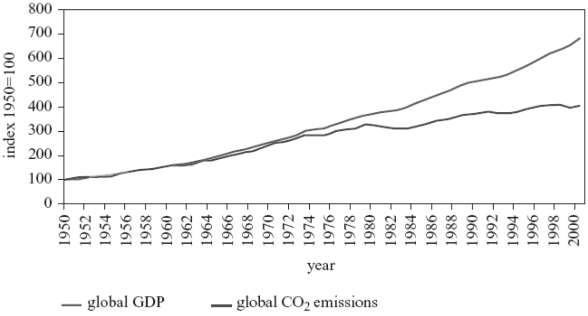
These efficiency processes intensified significantly after the 1970s, when energy price increases and the resulting perception of energy scarcity led to the adoption of technological strategies and policies to encourage energy conservation (Martin, 1990; Casler and Afrasiabi, 1993; Rosenberg, 1994, 1996). In some cases, decreasing intensity and greater energy efficiency derived from non-specific innovations.

These include changes in material use in some sectors which, as a result of lightness and dematerialization, have led to lower energy requirements for the same function. Similar developments towards greater use efficiency in relation to GDP have emerged for most industrial materials. In the case of minerals and metals – which have historically seen the coexistence of materials whose use intensity increased and decreased in relation to GDP – the 1970s represented a turning point, and the worldwide decline in use intensity has extended to almost all metals (Tilton, 1989; Considine, 1991; Labson and Cropton, 1993; Fortis, 1994). Towards the end of the 1990s, the decline in energy intensity slowed in many countries, which can broadly be attributed to decreases in the real prices of fossil fuels; however, this did not reverse the basic trend towards greater efficiency (see below).

Although this evidence supports the idea that there is a Kuznets curve for energy, the studies of EKCs have mainly concerned emissions of pollutants and the greenhouse effect, in connection with policies to combat climate change. The first studies on the relationships between atmospheric emissions and income in the quest for a Kuznets curve date back to the early 1990s (Holtz-Eakin and Selden, 1992; Ten Kate, 1993; Grossman and Krueger, 1994; Selden and Song, 1994). These were followed by numerous studies debating the statistical-econometric aspects and the economic interpretation of environmental Kuznets curves (Yandle *et al.*, 2002), gradually calling into question the reliability of the empirical evidence[5].

In the case of CO_2 emissions from fossil fuels, the tendency to decouple from economic development has been studied with divergent results, both for individual countries and globally. This results partly from the small time span considered and from the fact that these studies deal with cross-country data for a limited number of years. On the other hand, if a long or very long time span is considered, such as that shown in **Fig. 1**, clear indications emerge, at least on the global level.

Fig. 1. Dynamics of real global GDP and CO_2 emissions from fossil fuels.



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[5] For some environmental problems, such as waste production, there is no evidence for progress in line with a Kuznets curve (Mazzanti and Zoboli, 2005a).

This shows that CO_2 emissions from fossil fuels have decoupled from global GDP since the 1970s, reflecting the structural changes which had occurred for energy. However, emissions continue to increase and the decoupling is therefore ‘relative’, i.e. a decrease in emission intensity, rather than ‘absolute’. This is due to the impact of other macrofactors such as population and real *per capita* income, which have not been offset enough by increased efficiency. Albeit with some differences, this is the situation in most individual countries.

Figs. 2 and **3** show the same processes in a very long term perspective, from 1870 to 2000, in terms of Kuznets curves[6]. Emissions continue to increase as real global GDP grows, although to a lesser extent, and there is thus no Kuznets curve for emission levels. However, an EKC relationship does appear to exist for emissions intensity, which presents a roughly inverted U compared to real GDP, as predicted by the theory. If efficiency represents the state of technology, innovations and structural changes in economic systems have had continuous and significant effects over the past fifty years, but these remain insufficient compared to the demand for innovation needed to stabilize or decrease the level of emissions.

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[6] In Figs. 2 and 3, the data on emissions from fossil sources are those produced by CDIAC (Carbon Dioxide Information Analysis Center). The data on GDP are drawn from the OECD (Organisation for Economic Co-operation and Development) database. The data published by the OECD for real global GDP are estimates by Angus Maddison for the years 1870, 1900, 1913 and time series from 1950 to 2000. The data for the years 1871-1899 and 1901-1912 are our extrapolations based on the assumption of a constant average annual growth rate between the two available years. The data for the period 1914-1949, given the instability of the world economy during this period, which makes a constant growth rate an unrealistic assumption, are our estimates. It has been assumed that global GDP is proportional, in every year of the range, to the total GDP of a set of 44 countries in Maddison’s database, representing 68% of global GDP in 1913 and 71% in 1950. It should be noted that the same countries, including the major industrialized nations, account for between 68% and 71% of global GDP for the whole period 1950-2000

Fig 2. Global CO_2 emissions from fossil fuels vs. global GDP levels between 1870 and 2000.

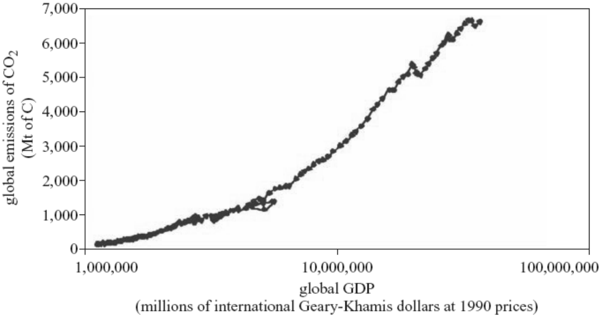
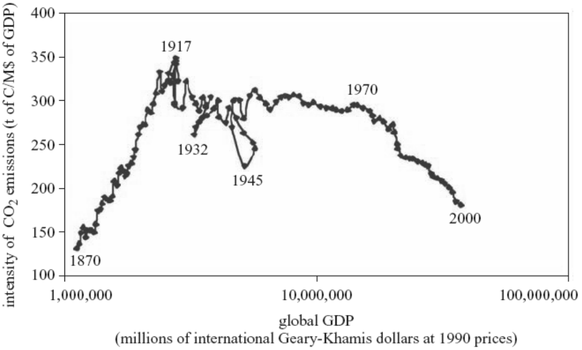


Fig 3. Intensity of CO_2 emissions from fossil fuels vs. global GDP levels between 1870 and 2000.



6. The mechanisms of technological innovation for energy and the environment

The trend of the indicators examined above suggest the working of innovation for natural resources, but only offer an implicit explanation of the mechanisms by which innovation itself emerges and operates. If, on the one hand, innovation for energy and emissions conforms to normal innovation mechanisms (Malerba, 2000), on the other, it also concerns the use of scarce resources and therefore conforms to the model of
"innovation scarcity" outlined in Chapter 1.2. Specifically, the innovation is influenced by: *a*) specific signs of relative scarcity emerging from the markets and prices that possibly lead to specific resource-use innovations; *b*) the numerous public policies adopted by all countries in these sectors; *c*) macroeconomic dynamics and structural changes in economic systems; *d*) general innovations in other fields. In turn, innovative processes for resources influence all these sectors to some extent.

The hypothesis of 'induced innovation', originally formulated by John Hicks in the 1930s in the contextof economic macrodynamics, is currently being rediscovered and applied to the impact of markets and prices on innovation[7].

This hypothesis suggests that a change in the relative prices of factor inputs tends to generate technological innovation which reduces the use of the factor whose price has increased relative to that of other factors.

This hypothesis provides results not dissimilar to those of the multisectoral models of rents, growth and the distribution of income described in Chapter 1.2, although quantity variables play a central role in the dynamics theorized in the latter (Quadrio Curzio and Pellizzari, 1996, 1999). The Hicksian induced innovation hypothesis has had numerous theoretical and applied developments in the recent past (Ruttan and Hayami,

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[7] More precisely, the Hicksian hypothesis refers to 'induced invention' (Hicks, 1985).

1985; Kemp, 1997; Ruttan, 2002; Mazzanti and Zoboli, 2005b, 2006), and has been reproposed by numerous recent models of ‘endogenous innovation’ applied to energy and climate policies (Carraro *et al*., 2003).

The discussion below will cover two specific contexts where the hypothesis of induced innovation may apply: the role of prices on energy efficiency and the role of public policies, especially climate change policies, on emissions efficiency.

6.1. Relative prices and technological innovation

The exceptional increases in energy and raw materials prices in the 1970s resulted not only in structural changes in economies and innovative processes of a systemic nature with an impact on the overall efficiency of resource use, but also in specific induced innovations aimed at conserving the resources which the markets indicated to be scarce (Quadrio Curzio, 1983; Sylos Labini, 1984; Quadrio Curzio et al., 1994; Mokyr, 1995; Quadrio Curzio and Zoboli, 1995a,b; Rosenberg, 1996; Quadrio Curzio and Zoboli, 1997; Popp, 2002).

The interpretation of relative energy prices as the main driving force towards energy-related innovations, however, has been undermined by events over the past two decades. The fall in the real prices of energy after the mid-1980s has not led to an inverse innovation process in which energy, now less scarce, replaces other production factors. Again, using general indicators, **Fig. 4** shows that the strong price increase in the 1970s led to a decline in the intensity of CO2 emissions from fossil fuels, closely linked to the consumption of primary energy; however, the fall in real prices which followed did not change the declining trend of energy-emissions intensity, which still continues.

Although this pattern may be influenced by expectations regarding climate policies, which might have prevented abandoning the paths of energy-emission saving, efficiency’s inertia is too strong for it not to have more structural explanations.

Whereas in a narrow neoclassical economics view, this lack of symmetry would argue against relative prices playing a crucial role, in a structural and evolutionist view, this may be an important indication of the nature of induced innovation processes in the presence of fixed capital.

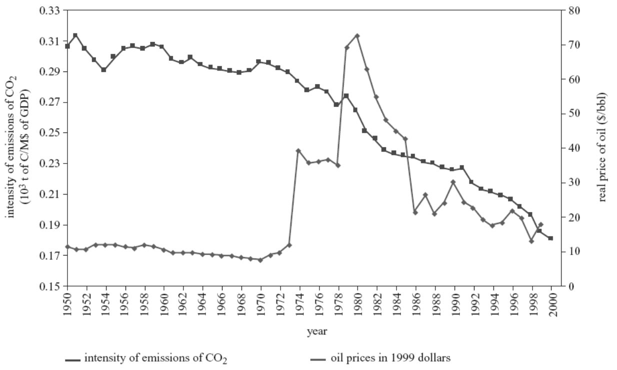

Fig 4. Real energy prices and intensity of CO_2 emissions between 1950 and 2000.

Most innovations which conserve energy and raw materials are incorporated in medium and long-term capital goods (such as industrial plants, vehicles and houses); this may explain both a degree of slowness in the adoption and diffusion of currently available energy efficiency solutions, and the poor reversibility, for a considerable time, of the efficiency gains acquired.

Analysing energy efficiency mechanisms over the long term, Rosenberg (1994) suggests that even if different energy sources can be easily substituted with each other, and it is possible to conserve energy without significantly altering processes and products, the attainment of a greater energy efficiency always requires some capital investment. As a consequence, increases in efficiency tend to be slow despite the availability of energy conservation technologies and the strong pressure to conserve exerted by markets and prices. The reason is that although these

technologies meet the criterion of lowering the specific costs of energy inputs, they do not lower total costs since they entail investment costs. Only in proximity to capital renewal cycles and/or when energy prices are extremely high and expected to remain so for a long
time, is the adoption of these technologies beneficial in terms of total costs.

Mechanisms of this type emerge with great complexity in the construction sector, whose energy consumption accounts for about 40% of the European Union (EU) total. The adoption of available energy saving technologies in constructions could lead to a reduction of a fifth compared to current levels[8].

However, in this sector, numerous variables affect decisions to invest in efficiency, the agents making these decisions are heterogeneous, and there are difficulties in measuring efficiency compared to other sectors. For new buildings, the decision to incorporate energy efficiency is taken by the builder or by the
owner. In both cases, the fundamental economic problem is to get the market to recognize the property's increased value due to the investment in efficiency, which leads to lower consumption and cost savings throughout the property's useful life.

Investment in retrofitting constitutes a fundamentally different problem from an economic standpoint, since this entails choosing when to make the investment, if it is worth making at all. Generally speaking, current energy prices have more impact on this type of investment than future prices. This is because they influence total costs during the possible period of non-adoption, which is closest to the present and thus more weighted, since costs are discounted to present value. The interesting aspect of retrofitting costs is that if they are expected to fall sufficiently fast in the future, retrofitting is postponed. Therefore, even if the present value of expected energy savings is higher than the present cost of retrofitting (i.e. if the net benefit is positive), the

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[8] This would be equivalent to a 10% saving in net imports of petroleum products, and a reduction in greenhouse gas emissions equal to 20% of the EU's commitments in the Kyoto Protocol.

technology may not be adopted if technological innovation is continuous and fairly rapid, or if future public incentives (which reduce adoption costs) are expected to be higher than current ones (Jaffe and Stavins, 1994).

This example shows that not only current prices but also expectations regarding prices may play a significant role in the substitution of capital with other capital that incorporates greater efficiency. Even if these price expectations later turn out to be wrong, with lower cost savings than those expected due to falling prices, once greater efficiency is attained, it is still more expensive to return to lower efficiency than to maintain that acquired; this is since the energy saved has a positive value, regardless of its price. If strong price increases have induced investment in capital which incorporates efficiency, a change which produces lower signs of scarcity (i.e. a price decrease) may slow down the adoption and diffusion of efficient technologies, but is unlikely to lead to a reverse towards lower efficiency. This is all the more true for changes like those which took place after the 1970s, which radically reconfigured advanced technological and economic systems. Specifically, the greatest inertia of efficiency is shown by long-lived capital and that which is most interconnected through infrastructure systems; this is true both for processes of adoption and of substitution with other technologies (Gruebler *et al.*, 1999). To this should be added the cumulative learning processes associated with the market expansion of new technologies, which reduce costs and consolidate positive economic returns, even when there are changes in relative prices that are unfavourable to the newly-adopted technology.

Explicit investments in research and development, and in new innovations follow similar paths. Only stable favourable conditions, such as increases in energy prices believed to be lasting, trigger the process of investment in the research and development of new technologies up to the commercial stage. After this stage, there is a gradual diffusion of new technologies that follows logistic models (take-off, maturity, saturation and decline). As such, relative energy prices may act – to use Rosenberg's terminology – as 'focusing devices', mechanisms which identify the most valuable areas of research and development and innovation. Except under extreme conditions of change, each cluster of innovations tends to start with earlier efficiency standards and raise them, partly driven by long-term research and development programmes, such as those of the European Union, which do not respond immediately to changes in economic variables. The current state of the energy market mainly has an impact on new research and innovation programmes, leading to different priorities in the allocation of financial resources. This is obvious from the history of scant attention to programmes for renewable energy sources when oil prices are low (regardless of environmental pressure).

This interpretation of the irreversible effects and innovation inertia associated with strong or lasting changes in relative prices is also supported by evidence from historical price trends in real terms.

Although the debate remains open, there is increasing evidence for the existence of long-term declining, or not increasing, trends in the prices of most raw materials and energy sources. In contrast to the hypothesis of increasing resource scarcity, the drop in real prices over the long term suggests relative abundance. The latter, combined with continuous gains in use efficiency, may support the hypothesis of a one-directional technological dynamics of the type described above. In fact, strong signs of scarcity, through phases of high real prices, induce increases in efficiency. However, the subsequent decline in real prices does not cause increased intensity in the use of energy and materials, given the inertia of fixed capital and programmes of investment in innovation.

Efficiency thus tends to move in one direction towards the lower, more advanced, part of the Kuznets curve in accordance with mechanisms similar to those suggested by theories of growth stages, long waves and alternation between dominant technologies (Vasco, 1987; Rostow, 1990; Marchetti, 1991; Gruebler *et al*., 1999).

Similar efficient innovation mechanisms are also at work for the supply of resources. Even when real prices are falling, the supply of energy and raw materials continues to increase, supported by the need to compensate for falling prices with higher quantities and by innovations which reduce extraction costs, and thus allow producers to maintain their rents. The role of cost saving innovations in maintaining high supply levels in the petroleum sector is well known (IEA, 2001b).

In other words, the relative prices of energy and materials may act as initial driving forces in long-term dynamic processes which lead to changes in technological and production systems. These are capable of definitively changing the starting conditions to such an extent that subsequent inverse changes in relative prices do not have a symmetrical effect compared to increases. The unusual intensity of energy price changes during the 1970s may help to explain both the accelerated declining trend of energy intensities, and their non-reversal in response to the fall in real energy prices during the 1980s-1990s. However, it is true that the latter did decelerate innovation processes for efficiency, and this is an important issue for energy and climate change policies.

6.2. Climate policies and technological innovation

Despite their important role, changes in relative prices cannot be the only explanation for the observed innovation processes, since resources and the environment are subject to numerous public policies which influence the prices themselves, the quantities supplied and demanded, investments in research and development, and other variables.

Specifically, taxation and regulation policies have traditionally played an important role in filtering changes in energy prices, altering them both in an amplificatory and compensatory way. Furthermore, the average levels and structure of energy prices are heavily differentiated in different countries, since energy products are subject to a variety of forms of taxation unparalleled in other sectors. Given that demand is relatively inelastic in the short term, the main aim of energy taxation is to increase revenues.

However, the structure and level of prices determined by the tax burden may objectively have the effect of encouraging conservation and efficient technologies in the medium-to-long run or, conversely, may act as an implicit subsidy encouraging high consumption. In recent years, the emergence of concerns about the climate has become manifest in the introduction of energy-environmental taxes (in particular, Carbon-Energy Tax or CET) in various European countries.

Such policies may introduce scarcity signals which, in the case of environmental resources such as the climate, cannot be provided by the market, thus stimulating also technological innovation.

The current debate sees different positions on the economic and technological impact of energy-environmental policies (Jaffe *et al.*, 2003). On the one hand, the hypothesis of a "loss of productivity/competitiveness" states that: energy conservation and emissions reduction policies create opportunity costs for the production system; these policies depress growth and the competitiveness of the most environmentally advanced countries; innovations to meet policy requirements crowd out innovation in other more productive areas of technology. On the other hand, the "Porter hypothesis" (Porter and van der Linde, 1995) claims that: the investments induced by energy-environmental policies do not crowd out other investments; the policy-induced innovations can reduce compliance costs; investments in environmental innovation may generate competitive advantages for the technologies and products of the businesses which undertake them.

Essentially, the whole debate revolves around whether or not energy-environmental policies stimulate innovation, if the latter is economically advantageous in terms of net social costs and if it can generate new market areas for investors.

Although areas of agreement and dissent remain on this issue, the policy debate of the 1980s and 1990s led to a concentration on the costs and innovation effects (or the ‘dynamic efficiency’) of the objectives and tools adopted by the policies. Theory and empirical evidence suggest that the economic instruments have lower social costs than traditional policy instruments (restrictions on quantity, standards, controls, etc.) and may be more effective in stimulating innovation. In the case of energy and the climate, this first led to proposals to introduce carbon-energy taxes (CETs) and, subsequently, to proposals to create markets for tradable emissions permits (ET, Emissions Trading).

CET proposals in Europe date back to the 1980s and have met with strong resistance from some countries and economic stakeholders, based on the hypothesis of a loss of productivity/competitiveness.

They were sidelined after the Rio Conference in 1992, when the European proposal of a global carbon tax failed due to American resistance. Some European countries, however, have implemented domestic CETs.

In contrast to the enormous number of *ex ante* simulations of the impact of CETs on the economic and technological system, there are few *ex post* analyses of their impact, which tell us little about effects on innovation in practice (Baranzini *et a*l., 2000; Mazzanti and Zoboli, 2000). Generally speaking, it appears that this policy instrument has mainly had the effect of correcting the complex energy taxation system, with a dubious and probably negligible impact on both induced innovation and competitiveness.

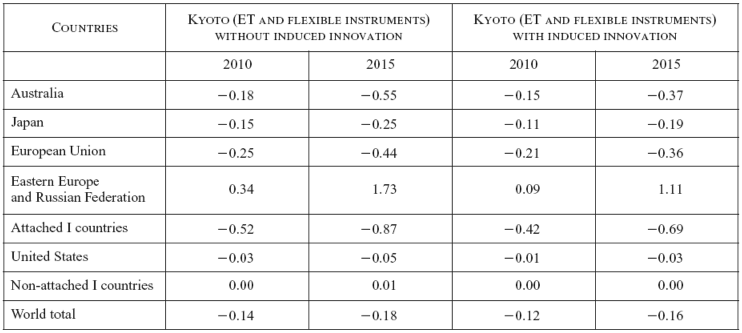
With the Kyoto Protocol, the emphasis has shifted towards the other main economic instrument for environmental policy, i.e. the creation of markets for tradable permits (in their two main forms, ‘cap and trade’, and ‘baseline and credit’). Initially proposed by the United States following numerous national applications to atmospheric pollutants, these instruments have become characteristic of the Kyoto Protocol and have generated a wide-ranging debate which is still open. After the refusal of the

United States to ratify the Protocol in 2001, the EU has taken the lead in implementing these instruments, up to the creation of the European Union Emissions Trading Scheme (EU ETS) for CO2 (Directive 2003/87/EC). The related Linking directive allows ETS operators to use carbon dioxide credits deriving from Joint Implementation (investments in Annex I countries, i.e. industrialized and transition countries) and Clean Development Mechanism (investments in non-Annex I countries, mainly developing ones) to comply with their obligations under the EU ETS.

The European scheme started in 2005 and involves about 12,000 businesses in the most emission-intensive sectors (from the production of thermoelectric power generation to the paper industry), accounting for about 40% of total emissions in the EU. With the EU ETS, which is the largest emission market in the world, the hitherto small global CO2 market has taken off, generating a reference price for CO2 and thus an opportunity cost for emissions. The latter makes it advantageous to adopt abatement technologies or technological innovations able to conserve energy and reduce emissions.

Also in the implementation of Kyoto instruments, induced innovation takes on a central role both in reducing the costs of attaining the objectives (**Table 1**) and in the possibility that Europe may play an important role in supplying efficient technologies to the global energy-environment system.

Table 1. Costs of the Kyoto Protocol: values (%) of GDP compared to the reference scenario with and without induced innovation (Criqui and Kitous, 2003)



COUNTRIES	KYOTO (ET AND FLEXIBLE INSTRUMENTS) WITHOUT INDUCED INNOVATION		KYOTO (ET AND FLEXIBLE INSTRUMENTS) WITH INDUCED INNOVATION	
	2010	2015	2010	2015
Australia	−0.18	−0.55	−0.15	−0.37
Japan	−0.15	−0.25	−0.11	−0.19
European Union	−0.25	−0.44	−0.21	−0.36
Eastern Europe and Russian Federation	0.34	1.73	0.09	1.11
Attached I countries	−0.52	−0.87	−0.42	−0.69
United States	−0.03	−0.05	−0.01	−0.03
Non-attached I countries	0.00	0.01	0.00	0.00
World total	−0.14	−0.18	−0.12	−0.16

Generally speaking, it can be expected that the EU ETS is cost-effective since it should lead to reductions in compliance costs (i.e. lower GDP losses) compared to other policy instruments with the same objectives.

However, it is not clear if and how it can actually produce high incentives for innovation. The task of allocating emissions quotas has been assigned to individual EU countries, albeit conditional on the approval by the Commission. In general, countries have set CO2 emission quotas in a way which is not particularly restrictive, thus pursuing low costs implementation for national industries (in line with the loss of productivity/competitiveness hypothesis) and with discretional allocations among the national industries involved.

The result is a certain global abundance of quotas compared to the Kyoto path; combined with an expected flow of low cost carbon credits from developing countries (from the implementation of the Linking directive) and Eastern Europe/Russia (so called ‘hot air’). This suggests a market development marked by low CO2 prices (from 6 to 15 €/tCO2eq according to the simulations[9]). These low carbon prices will be unable to induce significant investments in emission reduction,

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[9] tCO2eq: tonnes of carbon dioxide equivalent.

since they encourage operators to enter the market as purchasers of the reductions attained by others at a lower cost than their own reductions. The main effects on innovation will probably be limited to the adoption of existing technologies and their diffusion, partly on an international level through investments in joint implementation and clean development mechanisms.

Only once low-cost reduction opportunities have been exhausted will CO2 prices rise and signal scarcity, inducing greater pressure to innovate.

It is therefore uncertain if and when the development of the emission permits market will lead to innovations for energy and the environment in Europe, even compared to the United States. The latter's climate policy is explicitly targeted at technological programmes and emissions intensity objectives, although these are not particularly restrictive and thus, per se, do not represent a significant incentive.

The importance of energy-climate policy's function as a dynamic incentive for innovation is stressed by the various analytical models of the impact of Kyoto which adopt 'endogenous innovation' hypotheses. However, these models emphasize the numerous difficulties in understanding actual innovation mechanisms (Carraro *et al*., 2003). For this reason, if policy tools are insufficient to generate the necessary innovations, new and explicit research and development policies for energy and the climate should be activated; at the same time, the large research programmes already underway in Europe and individual countries should be strengthened (Popp, 2004).

From this point of view, it should be noted that energy and the environment are already of significant importance in European Union research programmes, with a specific budget of 4.8 billion of euro (10% of the total) in the VII Framework Programme currently underway, and may receive important input from other areas of innovation, such as materials and nanotechnologies. They also represent an important component of the National 2005-2007 Research Programme launched in Italy.

The possibility that innovation for the energy-climate may play a role in the Lisbon Strategy to make the Union’s economy more innovative is highlighted by the launch of the Environmental Technologies Action Plan (ETAP). The ETAP was adopted by the European Council in March 2004 (European Commission, 2005) and clearly espouses the viewpoint here described as the Porter hypothesis, when it stresses that: *a*) environmental technologies employ more than 2 million people in the EU; *b*) the impact of environmental policies on employment is neutral or positive; *c*) the negative effects of pollution control policies on competitiveness are limited; *d*) environmental innovations may generate international market opportunities, given the increasing involvement of large, rapidly developing countries such as China in global energy-environment policies, especially in the post-Kyoto scenario.

REFERENCES

Andreoni J., Levinson A. (2001), *The simple analytics of the environmental Kuznets curve*, «Journal of Public Economics», 80, 269-86.

Ayres R.U., Ayres L.W., Pokrovsky V. (2004), *On the Efficiency of US Electricity Usage since 1900*, Interim Report IR-04-027, IIASA, Laxenburg.

Baranzini A., Goldemberg J., Speck S. (2000), *A future for carbon taxes*, «Ecological Economics», 32, 395-412.

Carraro C., Gerlagh R., van der Zwaan B. (2003), *Endogenous technical change in environmental macroeconomics*, «Resource and Energy Economics», 25, 1–10.

Carter A. (1970), Structural Change in the American Economy, Harvard University Press, Mass.

Casler S.D., Afrasiabi A. (1993), *Input Composition and the Energy-Output Ratio*, «Structural Change and Economic Dynamics», Vol. 4, No. 2.

Chimeli A., Braden J. (2005), *Total factor productivity and the Environmental Kuznets curve*, «Journal of Environmental Economics and Management», 49, 366-80.

Considine T.J. (1991), *Economic and Technological Determinants of Material Intensity of Use*, Land Economics, 67-1, February.

Dasgupta P. (1982), *The Control of Resource*, Oxford, Basil Blackwell.

Dasgupta P., G. Heal (1971), *Economic Theory and Exhaustible Resources*, Cambridge, Cambridge University Press.

Dasgupta P.S., Heal G. (1974), *The optimal depletion of exhaustible resources*, «The Review of Economic Studies», 41: Special volume for the Symposium on the economics of exhaustible resources, 3-28.

Dasgupta S., Laplante B., Wang H., Wheeler D. (2002), *Confronting the Environmental Kuznets Curve*, «Journal of Economic Perspectives», 16, 147-68.

De Bruyn S., Van den Bergh J., Opschoor J. (1998), *Economic growth and emissions: reconsidering the empirical basis of EKC*, «Ecological Economics», vol. 25, pp. 161-75.

DEFRA/DTI (2003), *Sustainable Consumption and Production Indicators*, DEFRA, London.

Dinda S. (2004), *Environmental Kuznets Curve Hypothesis: A Survey*, «Ecological Economics», 49, 431-455.

EEA (2003), *Europe's environment: The third assessment*, Environmental assessment report No 10, Copenhagen: EEA.

Ehrlich P.R. (1971), *The population bomb*, Ballantine Books, New York.

European Commission (2005), *Report on the implementation of the Environmental Technologies Action Plan in 2004*, Brussels, 27.1.2005 COM(2005).

Fortis M. (1994), *Economic Growth and the Intensity of Use of Industrial Materials*, in A. Quadrio Curzio, M. Fortis and R. Zoboli (eds.), *Innovation Resources and Economic Growth*, Springer-Verlag, Berlin.

Grossman G.M. and Krueger A.B. (1994), *Economic Growth and the Environment*, NBER Working Papers, No. 4634, February.

Gruebler A., Nakicenovich N., Victor D.G. (1999), *Dynamics of energy technologies and global change*, «Energy Policy», 27, 247-280.

Hahn F.H., Matthews R.C.O. (1965), *The theory of economic growth: a survey*, in: American Economic Association-Royal Economic Society, *Surveys of economic theory*, London, Macmillan, 1965-1966, 3v.; v.II.

Harrod R.F. (1939), *An essay in dynamic theory*, «The Economic Journal», 49.

Harrod R.F. (1948), *Towards a dynamic economics*, London, Macmillan.

Hicks J. (1985), *Methods of Dynamic Economics*, Claredon Press. Oxford.

Holtz-Eakin D., Selden T.M. (1992), *Stoking the Fires? CO2 Emissions and Economic Growth*, NBER Working Papers 4248.

Hotelling H. (1931), *The economics of exhaustible resources*, «The Journal of Political Economy», 39, 137-175.

IEA (1997), *Indicators of energy use and efficiency*, OECD/IEA, Paris.

IEA (2001a), *Energy indicators and sustainable development*, OECD/IEA, Paris.

IEA (2001b), *World Energy Outlook: Assessing today's supplies to fuel tomorrow's growth*, IEA, Pairs.

Jaffe A.B., Newell R.G., Stavins R.N. (2003), *Technological Change and the Environment*, in Mäler K-G. and Vincent J.R. (eds.), *Handbook of Environmental Economics. Volume 1*, Elsevier, Amsterdam.

Jaffe A.B., Stavins R.N. (1994), *The energy paradox and the diffusion of conservation technology*, «Resource and Energy Economics», 16, 91-122.

Jaffe A.B. *et al.* (2003), *Technological change and the environment*, in: Mäler K.-G., Vincent J.R. (edited by)*Handbook of environmental economics.* Amsterdam, Elsevier, 3v.; v.I: *Environmental degradation and institutional*.

Jevons W.S. (1865), *The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines*, London, Macmillan.

Kemp R. (1997), *Environmental policy and technical change: a comparison of the technological impact of policy instruments*, Cheltenham, Elgar.

Keynes J.M. (1936), *General theory of employment interest and money*, London, Macmillan.

Kuznets S. (1990), *Popolazione, tecnologia, sviluppo*, Bologna, Il Mulino.

Kuznets S. (1955), *Economic growth and income inequality,* «The American Economic Review», 45, 1-28.

Labson B.S., Cropton P.L. (1993), *Common trends in economic activity and metals demand: cointegration and the intensity of use debate*, «Journal of Environmental Economics and Management», 25, 147-161.

Leontief W. (1941), *The structure of the American economy, 1919-1929*, Cambridge (MA), Harvard University Press.

Leontief W. (1951), *The structure of the American economy, 1919-1939*, New York, Oxford University Press.

Leontief W. (1953), *Domestic production and foreign trade. The American capital position re-examined*, «Proceedings of the American Philosophical Society», 97, 332-339.

Leontief W. *et al*. (1977), *The future of the world economy*, New York, Oxford University Press.

Malerba F. (a cura di) (2000), *Economia dell'innovazione*, Roma, Carocci.

Malthus R. (1798), *An essay on the principle of population*, London, Johnson.

Marchetti C. (1991), *The future*, International Institute for Applied Systems Analysis, RP-91-5, May.

Martin J.M. (1990), *Energy and technological change. Lessons from the last fifteen years*, «Science, Technology and Industry Review», July.

Mazzanti M., Zoboli R. (2000), *The application of carbon-energy tax in Italy and other European countries*, in: Confindustria-IPA-IRS, *Rapporto energia*, Roma.

Mazzanti M., Zoboli R. (2005a), *Delinking and Environmental Kuznets Curves for waste indicators in Europe*, «Environmental Sciences», December, 409-425.

Mazzanti M., Zoboli R. (2005b), *The drivers of environmental* *innovation in local manufacturing systems*, «Economia Politica», 3, 399-438.

Mazzanti M., Zoboli R. (2006), *Economic instruments and induced innovation. The European policies on end-of-life vehicles*, «Ecological Economics», 58, 318-337.

Meadows D.H. *et al*. (1972), *The limits to growth. The first report to the Club of Rome*, New York, Universe Book.

Mill J.S. (1848), *The principles of political economy with some of their applications to social philosophy,* London, Parker.

Mokyr J. (1995), *Environmental crises and technological change*, in: Quadrio Curzio A., Zoboli R. (editors) *Science, economics, and technology for the environment*, Milano, Cariplo Foundation for Scientific Research.

Neher P.A. (1990), *Natural Resource Economics: Conservation and Exploitation*, Cambridge, Cambridge University Press.

Neumann J. von (1945-1946), *A model of general economic equilibrium*, «The Review of Economic Studies», 13.

OECD (Organization for Economic Cooperation and Development) (2002), *Indicators to measure decoupling of environmental pressure from economic growth*, Paris, OECD.

Pasinetti L. (1965), *A new theoretical approach to the problems of economic growth*, Città del Vaticano, Pontificiae Academiae Scientiarum Scripta Varia.

Pasinetti L. (1977), *Dalla dinamica classica alla dinamica keynesiana*, in: *Sviluppo Economico e distribuzione del reddito: saggi di teoria economica*, Bologna, Il Mulino.

Pasinetti L. (1981), *Structural change and economic growth*, Cambridge, Cambridge University Press.

Popp D. (2002), *Induced innovation and energy prices*, «The American Economic Review», 92, 160-180.

Popp D. (2004), *R&D subsidies and climate policy: is there a "free lunch"?*, National Bureau of Economic Research, Working Papers 10880.

Porter M.E., Linde C. van der (1995), *Towards a new conception of the environment-competitiveness relationships*, «Journal of Economic Perspectives», 9, 97-118.

Quadrio Curzio A. (1967), *Rendita e distribuzione in un modello economico plurisettoriale*, Milano, Giuffré.

Quadrio Curzio A. (1983), *Primary commodity prices, exhaustible resources and international monetary relations: alternative explanations*, in: *Distribution, effective demand and international economic relations. Proceedings of a conference held by the Centro di studi economici avanzati, Trieste*, London, MacMillan.

Quadrio Curzio A. (1986), *Technological scarcity: an essay on production and structural change*, in: Baranzini M. and Scazzieri R. (editors), *Foundations of Economics - Structures of inquiry and economic theory*, Basil Blackwell, pp. 311-338.

Quadrio Curzio A. (1997), *Rendita*, in: *Enciclopedia delle Scienze Sociali Treccani*, Roma, Istituto della Enciclopedia Italiana Treccani, 1991-2001, 9v.; v. VII, 395-407.

Quadrio Curzio A. (1998), *Risorse e rendita: un contributo teorico con premesse storiche*, «Il Risparmio», 3, 417-441.

Quadrio Curzio A., Antonelli G. (1998), *The Agro-technological System Towards 2000* (editors), North Holland, Amsterdam.

Quadrio Curzio A., Pellizzari F. (1981), *La teoria economica delle risorse naturali: una storia sofferta e imbarazzante ma aristocratica e creativa*, «Energia», 2, 14-29.

Quadrio Curzio A., Pellizzari F. (1996), *Risorse, tecnologie, rendita*, Bologna, Il Mulino.

Quadrio Curzio A., Pellizzari F. (1999), *Rent, resources and technology*, Berlin, Springer.

Quadrio Curzio A., Zoboli R. (a cura di) (1995a), *Ambiente e dinamica globale. Scienza, economia e tecnologie a confronto*, Bologna, Il Mulino.

Quadrio Curzio A., Zoboli R. (editors) (1995b), *Science, economics and technology for the environment*, Milano, Quaderni della Fondazione Cariplo per la Ricerca Scientifica.

Quadrio Curzio A., Zoboli, R. (1997), *The costs of sustainability*, in: *The 50th anniversary of the United Nations and the Italian contribution toward the realization of the "Earth Charter". Proceedings of the conference*, Rome (Italy), Accademia Nazionale delle Scienze detta dei XL, May 1996.

Quadrio Curzio A. *et al.* (editors) (1994), *Innovation, resources and economic growth*, Berlin, Springer.

Quadrio Curzio A. *et al.* (1996), *Materie prime*, in: *Enciclopedia delle Scienze Sociali Treccani*, Roma, Istituto della Enciclopedia Italiana Treccani, 1991-2001, 9v.; v.V, 559-575.

Ray G. (1983), *Il contributo della scienza e della tecnologia all'offerta di materie prime industriali* (part I and II), «Materie Prime», n. 1/1983 e n. 2/1983.

Rosenberg N. (1982), *Inside the Black Box, Technology and Economics*, London, Cambridge University Press.

Rawls J. (1971), *A theory of justice*, Cambridge (MA), Harvard University Press.

Ricardo D. (1817), *On the principles of political economy and taxation*, London, John Murray.

Rosenberg N. (1994), *Energy efficient technologies, past and future perspectives*, in: Quadrio Curzio A. *et al.* (editors) *Innovation, resources and economic growth*, Berlin, Springer.

Rosenberg N. (1996), *The impact of technological change on resources for growing population*, in: Colombo B. *et al.* (editors) *Resources and population*, Oxford, Claredon.

Rostow W.W. (1990), *Theorists of economic growth from David Hume to the present with a perspective on the next century*, New York, Oxford University Press.

Ruttan V.W. (2002), *Sources of technical change: induced innovation, evolutionary theory and path dependence*, in: Gruebler A. et al. (editors) Technological change and the environment, Washington (D.C.), Resources for the Future, 9-39.

Ruttan V.W., Hayami Y. (1985), *Agricultural development: an international perspective*, Baltimore (MD), The Johns Hopkins University Press.

Schumpeter J.A. (1949), *The theory of economic development*, Cambridge (MA), Harvard University Press.

Selden D.H., Song D. (1994), *Environmental quality and development: is there a Kuznets curve for air pollution* *emission?*, «Journal of Environmental Economics and Management», 27.

Smith A. (1904), *An inquiry into the nature and causes of the wealth of nations*, London, Methuen, 2v.

Solow R.M. (1956), *A contribution to the theory of economic growth*, «Quarterly Journal of Economics», 70, 65-94.

Solow R.M. (1974a), *The economic of resources or the resources of economics*, «The American Economic Review», 64, 1-14.

Solow R.M. (1974b), *Intergenerational equity and exhaustible resources*, «The Review of Economic Studies», 41: Special volume for the Symposium on the economics of exhaustible resources, 29-45.

Sraffa P. (1960), *Produzione di merci a mezzo di merci*, Torino, Einaudi.

Stern D. (2004), *The rise and fall of the Environmental Kuznets Curve*, «World Development», 32, 1419-1439.

Stiglitz J.E. (1974), *Growth with exhaustible natural resources: efficient and optimal growth paths*, «The Review of Economic Studies», 41: Special volume for the Symposium on the economics of exhaustible resources, 123-137.

Sylos Labini P. (1984), *The forces of economic growth and decline*, Cambridge (MA), MIT Press.

Ten Kate A. (1993), *Industrial development and environment in Mexico*, The World Bank, Washington (D.C), Policy Research Working Papers 1125.

Tilton J.E. (1989), *The new view on minerals and economic growth*, «The Economic Record», 65, 265-278.

Tilton J.E. (1991), *Material Substitution: The Role of New Technology*, in: Nakicenovic N. Grubler A. (eds.), *Diffusion of Technology and Social Behavior*, Berlin, Springer-Verlag.

Vasco T. (editor) (1987), *The long-wave debate*, Berlin, Springer.

Yandle B. *et al.* (2002), *The Environmental Kuznets Curve. A primer*, Bozeman (MT), PERC Research Study 02-01.

Zhang Z. (2000), *Decoupling China's carbon emissions increase from economic growth: an economic analysis and policy implications*, «World Development», 28, 739-752.

Zoboli R. (1996), *Technology and changing population structure: environmental implications for the advanced countries*, «Dynamis-Quaderni», 6.

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