PSL Quarterly Review

vol. 76 n. 304 (March 2023)

Article

Exploitation of natural resources and the low-carbon switching of techniques inside linear production schemes

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Abstract:

The present work investigates the links between Ricardian and Sraffian economic analyses and the emerging themes of ecological macroeconomics, namely the impact of global warming and ecological or natural crises, the depletion of non-produced material resources, and the energy transition. The objectives of the work are: (a) to introduce the foundations of ecological economics through a simple representation of Ricardo's economic theory of the falling rate of profit (i.e., the stationary state), explaining the socio-economic impact of ecological crises linked to production process (global warming, land pollution, flooding, etc.) and of the shrinkages in the supply (extraction) of non-produced factors like energy materials (oil, coal, liquefied natural gas, etc.); (b) to evaluate the institutional conditions that must be met to make the energy transition from fossil fuels to renewable resources economically meaningful when capital accumulation is the main driver of economic growth; and (c) to broaden the field of research and perspectives within heterodox approaches to ecological macroeconomics by introducing new foundations based on modern Classical political economy.

How to cite this article:
Oro G. (2023), "Exploitation of natural resources and the low-carbon switching of techniques inside linear production schemes", *PSL Quarterly Review*, 76 (304): 3-19.

DOI: https://doi.org/10.13133/2037-3643/17838

JEL codes:
B51, E11, Q57

Keywords:
ecological crises, embodied energy, exhaustible resources, low-carbon energy transition

Journal homepage:
http: //www.pslquarterlyreview.info

1. Socio-economic aspects of ecological crises

Global warming, together with the Covid-19 crisis, has led most of the scientific and political communities to pay attention to the environmental sustainability of production and commercial processes and, consequently, to the energy transition from fossil fuels to renewable resources. In particular, the ecological macroeconomic literature from the post-Keynesian viewpoint has been based on three main principles (Sawyer and Fontana, 2013; Fontana and Sawyer, 2016; Carnevali et al., 2021). The first is that economic growth is driven by effective demand; the second is that, in the long run, constraints may emerge on the supply

* The author thanks Stefano Perri, Enrico Bellino, Giorgio Gattei, and the anonymous referees for their useful comments and suggestions. The responsibility of eventual errors remains with the author.

side due to *ecological crises* (environmental damages, land pollution, global warming, flooding, etc.) and to the *shrinkages in the supply of non-produced material energy factors*; and the third is that there are strong interconnections between the economic system, the social environment, and the ecosystem. Indeed, as argued by Fontana and Sawyer (2016), economic growth has a dual face: on the one hand, it is beneficial for social well-being and employment, but on the other hand it tends to accelerate the depletion of natural energy resources and therefore exposes the system to supply shrinkages.

James O'Connor (1998) translates the Marxian theory of the economic crisis into a theory of ecological crisis. Environmental damage leads the economy to suffer from the increasing material and social costs of production that lead to the "unproductive" use of capital and labour, both of which must be employed to cover the damage inflicted by the crises. Another point emphasized by O'Connor is that, since the work activity (necessary to produce new value) is inseparable from the women and men who carry it out, the ecological crises that affect the reproducibility of workers (earthquakes, floods, pollution, etc.) can lead to realization crises due to both the under-consumption of workers and their possible "resistance" to poverty and also to unjust standards of living determined by the environmental impact of production.

We also observed the growing interest in the energy transition and the different technical and political strategies aimed at achieving it. A recent study by the Centro Europa Ricerche (CER, 2022) states that it is neither certain nor immediate that the energy transition will lead to a reduction in production costs and a higher degree of competition in the market of energy resources. It is clear, in fact, that the subject touches many spheres of the economic and social systems.

From the point of view of the technical boundaries of the supply chain, the energy transition towards renewable resources would require more material inputs, which of course would increase the costs of production (an electric car requires, on average, six times the physical quantity of minerals necessary to produce a conventional vehicle, while a wind power plant requires nine times the amount of minerals required by a natural gas plant). Therefore, the technical-energy transition must respect certain economic conditions to make the transition accessible and economically sustainable if the basket of energy needs is to be maintained in both volume and composition.

From the point of view of competition in the market of exhaustible resources, the CER warns that the physical materials that are required during and after the energy transition of production processes are traded by fewer countries (especially those that do not benefit from political stability). The economy could therefore reach even higher degrees of monopoly and certainly be exposed to inflation from imported energy factors. Furthermore, low degrees of competition inside these types of markets can expose the economy to international tensions and conflicts, such as those observed with the recent Russo-Ukrainian conflict, which highlighted the dependence of European countries on the Russian natural gas supply, especially during the period of energy inflation already underway from the immediate post-pandemic scenario.

The aim of the contribution is to investigate these critical issues in the light of the contributions of Ricardo and Sraffa. The discussion is organized as follows. Since we mainly focus on the normative level of economic analysis, we present the elements adopted in the argumentative scenarios that are based on a simple structural model of a growing economic system that runs under permanent full employment and where there is no government or foreign markets. Such a framework, elaborated by Pasinetti (1962), allows us to focus on the

institutional conditions that must be satisfied to guarantee certain macroeconomic equilibrium, such as steady growth and full employment. In this context, we are mainly interested in the link between ecological damage and the production process and in the compatibility of environmental sustainability and the market economy. We consequently show how the Ricardian theory of the stationary state can be explanatory to capture the causes and consequences of ecological crises linked to the production process (global warming, land pollution, flooding, etc.) and of the shrinkages in the supply (extraction) of non-produced productive factors like energy materials (oil, coal, liquefied natural gas, etc.). Lastly, through the extension of the Sraffian framework to a production of commodities by means of non-produced factors, we analyse the institutional conditions that must be met to make the low-carbon energy transition economically sustainable inside a monetary market economy and, consequently, we evaluate the space for political and social interventions aimed at encouraging, planning and implementing the transition from fossil fuels to renewable resources. A concluding note follows.

2. The basic framework

The present discussion is based on the structural model of a one-sector production economy (Pasinetti, 1962; Casarosa, 1978; Kurz and Salvadori, 1995; Duménil and Levy, 1999; Foley et al., 2019). Within the extreme level of abstraction of an economy with only one productive sector (i.e., agriculture), since corn is both the only input and the only output of the economy, the correspondence between the commodity composition of the surplus and that of the means of production can be verified. This simplified picture is consistent with Ricardo's logic, according to the famous interpretation offered by Piero Sraffa of the *Essay on the Influence of a Low Price of Corn on the Profits of Stock* (Ricardo, 1951b). Such a level of abstraction is convenient for macroeconomic analyses and will be used here as a simple modelling tool for standard national income accounting.

Consider an economic system that grows at full capacity and at full employment. There is no government/taxation or trade in foreign markets, but only private agents. Producers use only circulating capital (the means of production must be replaced at each period, i.e., the depreciation of capital is assumed to be equal to unity) and, excluding landowners, i.e., the rentier class, two social classes (institutional sectors) coexist: the working class, which sells its labour power in exchange for a money wage that is assumed to be entirely spent on the consumption of wage goods, and the capitalist class, which owns the means of production and, on the basis of capitalist relationships such as property rights, is the only recipient of the profit that can be either spent on consumption or invested by purchasing capital goods (raw materials, machinery, etc.), which in this framework are simply corn used for the seeding.

2.1. Production system

The production of commodities occurs according to the dominant technological paradigm, which is defined by the fixed proportions of the inputs (capital and labour) necessary to produce a unit of output. The physical quantity produced can be accounted for as follows:

$$x = ax + y \tag{1}$$

We call x the physical quantity of the gross product or production, $a = K/x$ the technical coefficient of production that explains the quantity of the homogeneous good used as the means of production (K) per unit of output, and $y = (1 - a)x$ the quantity of commodities that makes up the social surplus, or net product (i.e., what remains after having subtracted from gross production all the goods necessary to replace the means of production) and consequently is made available for final uses, that is, consumption or investment. Equation (1) then solves:

$$x = (1 - a)^{-1}y \tag{2}$$

which shows a linear relationship between the commodities required for end uses and the gross product that results once the economy has set in motion the intermediate demand for inputs.[1] We can now estimate the inputs needed to meet the level of final demand. Calling $l = L/x$ the direct labour coefficient, which explains the number of workers (L) needed to produce a unit of output, we can write:

$$L = l(1 - a)^{-1}y = vy \tag{3}$$

and

$$K = a(1 - a)^{-1}y = ky \tag{4}$$

where v represents the vertically integrated labour coefficient, i.e., the amount of labour that is directly or indirectly required to produce a unit of final demand. In Ricardian terms this is *labour embodied* and k represents the coefficient of vertically integrated productive capacity of the system, i.e., the quantity of capital good that is directly and indirectly needed to produce one unit of final demand (Pasinetti, 1973, 1977).

Therefore, the dominant technological paradigm of the production system can be expressed using the fixed coefficients (embodied labour and productive capacity) that explain the technique available for the production of the homogeneous good (v, k). The meaning of the Leontief function is that, to produce a unit of social surplus in physical terms, producers need v units of labour (men, years, hours, etc.) and k units of capital.

2.2. Income distribution

We can now move to the distribution of income. The social classes participate in the distribution of national income, that is, the monetary value that firms obtain once the product has been sold during the market day and the means of production have been replaced. This means that the price of the net product essentially resolves into wages and profits:

$$py = WL + \pi pK \tag{5}$$

where p is the production price of the homogeneous good, W is the money wage per unit of labour and π is the rate of profit. Using equations (3) and (4) in (5) and after some algebraic

[1] The term $(1 - a)^{-1}$ is the one-sector formalization of the Leontief inverse, or the multiplier effect that captures the intermediate flows of input commodities that are activated in the economy to produce a certain basket of final goods.

steps, we can set the price of the homogeneous product equal to unity ($p = 1$) and obtain a linear and opposite relationship, for a given technique, between wages and profits:

$$\pi = \frac{py - WL}{pK} = \frac{1 - wv}{k} \tag{6}$$

where $w = W/p$ is the real wage.

In equation (6) emerges the antagonistic relationship over the distribution of income that exists between workers, who receive wages, and capitalists, who deduct profits and other capital incomes from the social product. To have economically meaningful solutions, i.e., positive wages and positive profits, we must assume that $w < 1/v$, the condition that the wage rate must be lower than net productivity of labour, and that $\pi < 1/k$, the condition that the profit rate must be lower than the output-capital ratio, i.e., the maximum rate of profit.[2]

2.3. Consumption patterns and accumulation regime

Classical political economy is based on "strong assumptions" about the consumption and investment behaviour of economic operators. In particular, workers are assumed to spend all their income on consumer goods because, historically, wages are assumed to tend to subsistence levels. On the other hand, the capitalist class consumes and invests its profits. Therefore, the overall expenditure of the economy can be accounted as follows:

$$y = gK + cL = gky + cvy \tag{7}$$

where g is the overall growth rate of the economic system, which expresses the level of net investment (the quantity of newly produced capital goods) of each production period, and c is the total consumption per worker (of workers and capitalists).

As already mentioned, the capitalists are the only economic subjects who accumulate capital to expand the production of goods to make profits. Classical economists, unlike Keynes, do not clearly distinguish investment from saving and postulate that capitalists essentially choose the share of profits to be spent on consumer goods (especially luxuries) and the share that is to be allocated to accumulation. Formally, we can express aggregate investment with an accumulation function according to which capitalists essentially fix a share of total profits to be allocated for the purchase of new capital goods. Therefore, the accumulation regime of the economy, which defines the overall growth rate of the system, can be expressed as:

$$g = \beta\pi \tag{8}$$

where $0 < \beta < 1$ is the investment share of profits, which in Keynesian terms can be interpreted as the capitalists' propensity to save. Equation (8) is the Cambridge equation from the reversed viewpoint of Classical political economy, which means that economic growth is

[2] Note that the wage multiplied by the vertically integrated labour coefficient gives exactly the wage share of the net product ($wv = WL/py$). Consequently, the numerator of equation (6) gives the share of profit ($1 - wv$) that is directly related to the rate of profit. The economics of the profit rate is essentially based on both technical and institutional preconditions. Technical constraints are determined by embodied labour and productive capacity coefficients. The institutional conditions are instead expressed by the level of wages (w). The latter variable is determined outside the price system, in particular within the labour market, which will be drawn below.

directly driven by the distribution of income, notably by the level of the prevailing rate of profit for a given propensity to accumulate of capitalists.[3]

At this point, we can assume that total consumption is composed of wages, since they represent the entire consumption of the workers and the part of the profit that remains once the decisions on accumulation have been made by the capitalist class:

$$c = c_w + c_p \tag{9}$$

where c_w is the consumption of the workers and c_p the consumption of the capitalists. This formalization allows us to obtain a linear relationship between growth and consumption. Using equations (7) and (8), we can express total consumption as a residual variable:

$$c = \frac{1 - gk}{v} \tag{10}$$

The above expressions show that total consumption essentially depends on the growth regime of the economy. Profits are what remain of the social surplus after wages are paid, while consumption is what remains after the accumulation decisions of the capitalists have been made.[4]

Our model now has three main equations: (6), (8) and (10), and four variables: the rate of profit, the rate of growth, the consumption per worker, and the wage rate. In fact, we know that, given the rate of profit, we can obtain the growth rate of the economy and then subtract it from the net product to calculate the social consumption per worker. However, the rate of profit depends on the wage rate, which, as mentioned, is determined within the labour market.

2.4. The labour market

According to Ricardo, "the market price of labour is the price which is really paid for it, from the natural operation of the proportion of the supply and demand; labour is dear when it is scarce, and cheap when it is plentiful" (Ricardo, 1951a, p. 84). Thus, when the system grows faster than the reproductive speed of the labour force, the real wage can rise due to the increasing bargaining position of the workers; such a mechanism can be described as follows:

$$w = w_0[1 + \varphi(g - n)] \tag{11}$$

where g here is equal to the employment growth rate, n is the growth rate of the working population (labour force), φ is the elasticity coefficient of the wage relative to the difference

[3] In the light of Pasinetti's (1962) approach, which is based on the research for normative relations, the sentence according to which accumulation is financed by profits holds even if we relax the "strong assumption" according to which workers consume all their wages and do not save. In fact, Pasinetti demonstrates that the behavioural assumption about propensities to save is descriptive of the equilibrium situation, reinforcing the view that they are not necessary to get, for instance, to Kaldor's (1955) results.

[4] Since, by hypothesis, workers spend all their income on necessary goods and do not save/accumulate, the residual variable that adjusts to investment decisions actually becomes the consumption of the capitalists. Hence, we can write:

$$c_w = w \tag{10b}$$

and

$$c_p = \frac{1 - gk}{v} - w \tag{10c}$$

between the growth rate of employment and that of the labour force (with $\varphi' > 0$, and $\varphi(0) > 0$), and w_0 is the real wage level in the previous production period.

Ricardo then introduces the notion of the natural price of labour, that is "the price which is necessary to enable labourers, one with another, to subsist and to perpetuate their race, without either increase or diminution" (Ricardo, 1951a, p. 93). Following the Malthusian theory of population, Ricardo asserts that the rate of reproduction of the labour force depends on the level of real wage. As long as capital accumulation remains positive, real wages will not tend to gravitate towards the natural (subsistence) wage, because employment will continually be increasing with accumulation. The supply of labour varies in response to changes in the market wage relative to the natural (subsistence) wage. We can therefore express the labour force growth rate as follows:

$$n = \sigma\left(\frac{w - w_s}{w_s}\right) \tag{12}$$

where $\sigma > 0$ is the elasticity of the labour force growth rate to the percentage difference between the market wage and the subsistence (natural) wage, which according to Ricardo is historically determined by the customs of a certain society.[5] The working population grows when the real wage is above the subsistence level, which defines the minimum wage as the one that is "socially accepted", while it stagnates ($n = 0$) when the wage is at the subsistence level ($w = w_s$). Ricardo believes that the tendency of the wage is to be above subsistence during the accumulation process and to drop to the natural level when accumulation falls. The system can achieve and maintain a steady growth once the condition that the growth rate of capital (employment) must equal the growth rate of the labour force is satisfied:

$$g^* = n^* \tag{13}$$

The model is now complete. Finally, we have a growing economic system that dynamically adjusts along a path of full employment (or a constant unemployment rate) due to the macroeconomic relations that are put in motion in the labour market in reaction to any shock of exogenous variables.

2.5. Comparative dynamics

The configuration of the economy is, at this point, described by five relations:

a. The distribution of the social surplus between wages and profits, defined by equation (6).
b. The spending behaviour of social classes, summarized by the relationship between the profit rate and the growth rate, expressed in equation (8).
c. The allocation of the surplus between consumption and capital accumulation, described by equation (10).
d. The determination of the real wage according to the prevailing labour market conditions, described by equation (11).
e. The rate of growth of the labour force according to the percentage difference between the current real wage and the subsistence (natural) wage, defined by equation (12).

[5] For a more complete treatment of Ricardo's theory of wages and a clarification of the main controversies on its interpretation, consult Perri (1988).

Figure 1 – *Model solution*

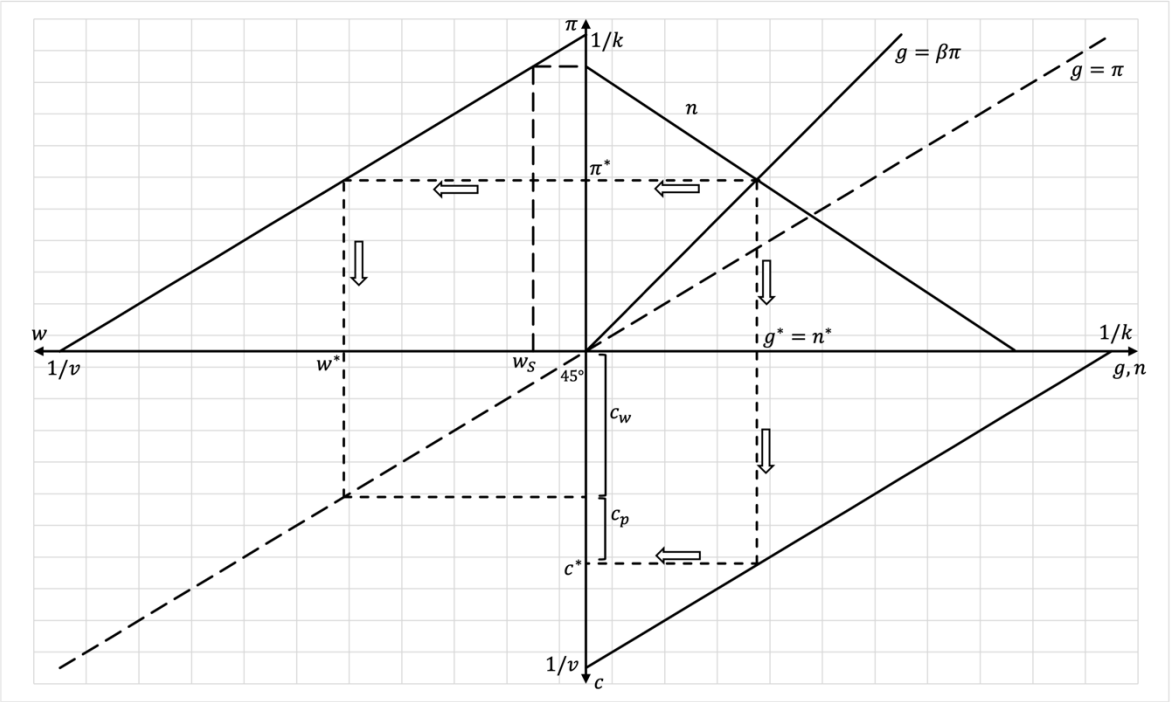


Figure 1 illustrates the model solution. The difference between the growth rate of capital and the growth rate of the labour force determines the real wage according to its elasticity to the rigidity of the labour market. The real wage, according to its distance from the given subsistence wage, determines the rate of profit. Consequently, social consumption is determined on the basis of the respective spending behaviours of the social classes. The growth of the equilibrium can be interrupted by shocks in the exogenous variables, which are the technical coefficients of production, the propensity for accumulation of the capitalists, the given subsistence wage, and the reaction parameter of the growth rate of the labour force to the percentage difference between the real and the subsistence wage.

The closure of the model, equations (11) and (12), represents the dynamic equilibrium in the labour market, which consequently regulates the path of the stationary state. The real wage therefore adapts elastically to the increase in employment. Consequently, the growth rate of the labour force varies according to the percentage difference between the market wage and its natural level. This labour market law is adopted by Ricardo on the basis of Malthus' population theory: high wages lead to an increase in the rate of reproduction of the population and therefore of the labour force (this is due to higher birth rates, higher immigration of workers, etc.). Conversely, when the wage is at the subsistence level, the working population tends to emigrate and, overall, the birth rate tends to decline.[6]

[6] While this might seem like a strong assumption, stylized facts suggest that, at least since the 1970s, the decline in the overall birth rate in developed economies has been associated with the decline in the wage share of national income.

3. Exploitation of natural resources and the Ricardian stationary state

Ricardo provides an undeniably pessimistic scenario of long-term economic development within capitalist economies. In his theory of the stationary state, Ricardo argues that, during the phases of rapid growth, wages can remain above the subsistence level, implying greater wellbeing for the society. High wages generally lead to an increase in the demand for wage goods due to employment growth. The need to expand the production of consumer goods leads the primary sector to exploit more natural resources. From the ecological viewpoint, climate change deriving from the exploitation of these resources can undermine the existing capital through the intensification of land and air pollution, deforestation, and natural disasters like earthquakes and flooding that may consequently occur. The issue can be explained with the definition of exhaustible resources and the implications of the depletion of such non-produced factors provided by Schefold:

> An exhaustible resource could be exhaustible in the strict sense that all accessible deposits where it was found could be depleted within a foreseeable future and that it was indispensable to production. We call this an irreplaceable commodity. […] The exhaustion of an irreplaceable commodity would be a catastrophe by definition since it would mean the collapse or at least the contraction of the system. […] Since a growing industrial society uses more and more materials that end up dissipated in the environment and that are not recycled through natural processes, increasing amounts of energy and labour have to be devoted to the recovery of such materials and to the correction of disturbed natural processes in soils, lakes, even the ocean and the air. […] The availability of the exhaustible resources is gradually modified by its extraction. This causes a slow rising of prices, which will affect all prices in the system (Schefold, 1989, p. 228).

These mechanisms can be modelled like a gradual fall in the returns on input factors in the primary sector. In Pasinettian terms, the labour and productive capacity required to produce one unit of surplus increase as accumulation (employment) in the primary sector increases; thus we can write:

$$v = v_{t0}(1 + g)^t \tag{14}$$

and

$$k = k_{t0}(1 + g)^t \tag{15}$$

where v_0 and k_0 are the vertically integrated coefficients of labour and productive capacity in the previous production period and the t apex stands for the number of periods to which the employment growth rate refers.[7]

The rate of profit begins to decline due to the increase in both the coefficients of labour and productive capacity, thus negatively affecting accumulation and economic growth. The reduced accumulation then lowers employment, leading to a decrease in wages until they converge, in the long period, at the subsistence level. Once the minimum wage is reached, the

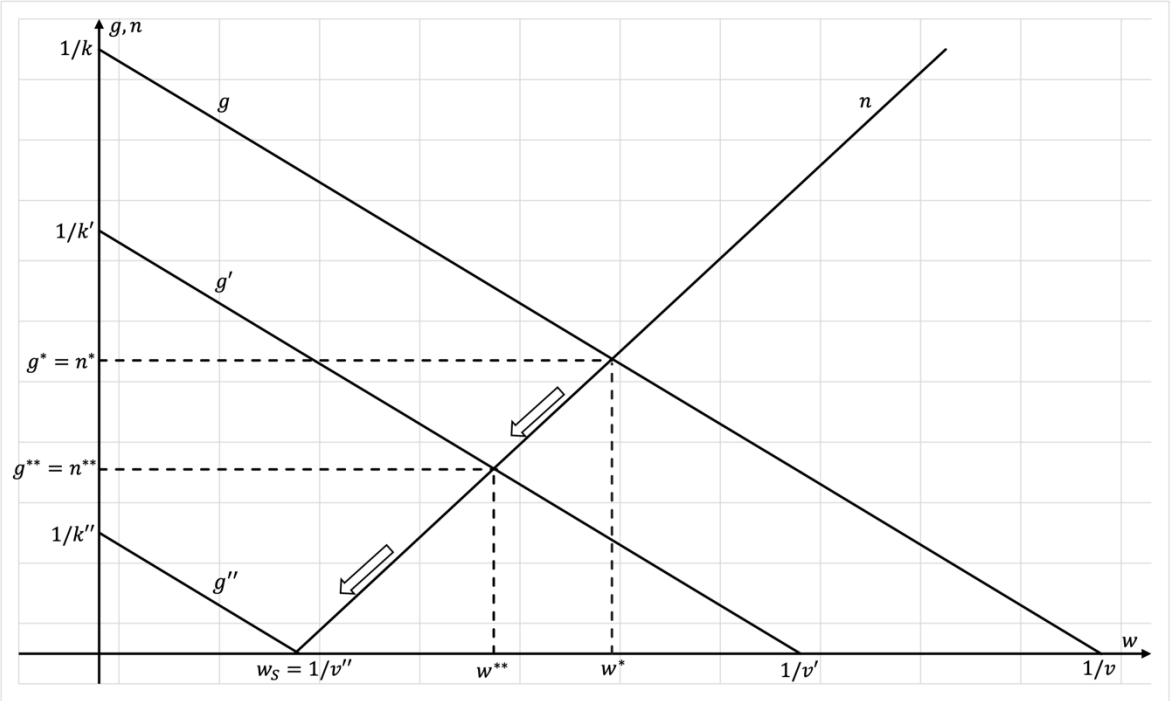
[7] The theoretical motive that is behind this formalization concerns the assumption that ecological damages and depletion of exhaustible resources are mainly driven by the capitalist mode of commodity production, given that it is based on profit accumulation. This does not mean that consumption behaviours do not affect the environment at all, as Di Bucchianico and Cappelli (2021) largely discuss; in fact, luxury consumption (like private jets and ships) have significant negative effects on the ecosystem and on the socio-economic system due to high pollution. However, we believe that the analysis of ecological feedback should focus, preliminarily, on the social function of the capitalist mode of production, which is not directly connected to the creation of use-values (final goods) but is oriented to the production of the exchange-values necessary for the formation of profit, which is only mediated by the production of use-values (Pirgmaier, 2021; Bellofiore, 2021). Therefore, we focus the analysis on capital accumulation and on the ecological feedback effects of production techniques.

working population stops growing and the accumulation process is interrupted as well. The Ricardian stationary state, within a linear model of production, shows the situation of a hypothetical Hicks-neutral technical regression, namely it happens that the returns of both capital and labour fall in parallel. The tendency of the economic system is therefore to move towards a situation in which

$$g^* = n^* = 0 \tag{16}$$

that is, when accumulation and population growth are zero because wages fall to the subsistence level. This is when, according to Ricardo, the economy experiences the stationary state.

Figure 2 – *A representation of the Ricardian stationary state*



A representation of this process is shown in figure 2. On the vertical axis we place the growth rates of capital and population, determined by equations (8) and (12), and on the horizontal axis the real wage, determined by equation (11). For a certain period of time, the economy is supposed to run in a high-accumulation regime that brings real wages above subsistence. The accumulation process then pushes producers to expand production, leading to the exploitation of more natural resources while in the meantime polluting the environment. During the process of capital accumulation, sooner or later, ecological crises can occur, decreasing both the labour productivity $(1/v)$ and the ratio of output per unit of capital $(1/k)$ in the primary sector. Therefore, capital growth shifts to the left and both the wage and the profit fall. Ecological crises and the depletion of material resources increase the requirements for labour and the means of production that guarantee the expansion of the economic system.

In our simplified framework, this means that the g curve progressively shifts down to g'. The growth rate of the labour supply adjusts accordingly until it reaches the new (and lower) growth rate ($g^{**} = n^{**}$), meeting the accumulation rate at a lower wage level (w^{**}). As the process of accumulation continues, in the absence of technological and ecological improvements that preserve the productivity of the primary sector (that could ultimately raise the returns on capital and labour or prevent them from falling), the economy could experience a further decline in returns until the growth rate shifts to g''. As a result, wages reach the subsistence level (w_s) and population growth drops to zero. At this point, the profit is zero as well, even if we do not see it from the graph, because the entire product of the economy (i.e., the primary sector) is allocated for the necessary subsistence consumption of the workers. In other terms, while the real wage decreases, the cost of labour increases due to the fall in labour productivity. In the situation described by Ricardo, the tendency of economic development is to be progressively limited by the exploitation of natural resources until the system reaches a period of economic stagnation, that is, the stationary state. Ricardo highlights two ways to escape the risk of economic stagnation: international trade and technological improvements.[8]

The first solution is based on the fact that, when a country tends to import raw materials from abroad instead of expanding domestic production, it could prevent the domestic primary sector from experiencing diminishing returns or, at least, produce a retarding effect on the tendency to stagnate due to environmental damages. In this way, the growth curve can be prevented from shifting downwards and real wages can remain above the subsistence level. In modern economies, however, when the supply-side constraints are considered, the problems could be multiple. Natural and exhaustible (non-renewable) materials are mainly produced/extracted and traded by the ownership of the natural resources (oil and natural gas wells), which ultimately sets the price of the commodity. This price, in turn, will reflect both the level of supply and the trader's monopoly position within the market for non-produced factors.[9] Therefore, economic dependence on foreign markets for this type of commodity implies an exposure of the economy to external trade deficits,[10] to imported inflation due to the rigidity of the market structure[11] and, last but not least, to international tensions and conflicts.

Technological progress, particularly in the manufacturing and energy sectors, is the most effective solution to the stationary state in all types of economies. It is not difficult to imagine how, for example, a technological change in the energy paradigm from fossil fuels to renewable resources can prevent the occurrence of diminishing returns, increasing the supply of energy to producers and consumers while preserving the environment from pollutive production process. Notably, fossil fuels are one of the raw materials that are exposed the most to supply

[8] Other elements are present in Ricardo's original formulation of his theory. First, when there is a decline in labour productivity in the consumer goods sector, the real cost of labour per unit of output increases for a given level of wages earned by workers. Another point is that, when less productive land and mines are used, the differential rent on the productive ones increases. We do not see this because, implicitly, the model refers only to the "marginal land". This means that, even if the real wage falls due to an accumulation rate lower than the population growth rate, the profit rate is squeezed by the increasing real labour costs (i.e., the price of wage goods) and by the increase of the differential rent on productive assets.

[9] Non-produced factors are defined as those material inputs that are necessary for production purposes but, unlike the commodity inputs and similar to labour, are not endogenously reproducible within the economic system. The category includes natural and exhaustible resources, which have a fixed or semi-fixed supply (i.e., with a reproducibility rate close to zero or subject to monopoly decisions) and that are exempt from land restrictions.

[10] A fixed level of import required by production and consumption implies that the trade deficit must be offset by at least an equal level of surplus in the other financial balances, i.e., private and public.

[11] This was the case with the oil inflation crisis of the 1970s in Europe.

shrinkages linked to increasing energy requirements of the productive process, in addition to creating pollution, the main cause of global warming. Innovations in the energy paradigm that are oriented towards environmental sustainability and saving of non-produced factors can remove or move away the "environmental frontier", meaning that they can pass through the ecological crises and the shrinkages in the monopoly supply.

Ricardo's painting from an ecological viewpoint provides an interpretative framework of many of the criticalities that are today linked to the most current events concerning environmental issues (global warming, pollution, flooding, etc.), raw material provisioning, and the low-carbon energy transition. In this way, we can get a picture of the fundamentals of *ecological political economy*:

a. *Interconnections between the ecosystem and the economic system*. Capital accumulation can harm the environment through pollutive productive processes. Therefore, ecological crises are more likely to occur (global warming, soil and air pollution, earthquakes, flooding, etc.) that, in turn, affect the socio-economic system by increasing the cost of living and the costs of production. Consequently, the lowering of living standards due to environmental damages can have repercussions on economic growth and on the people's health, up to lowering the birth rate and hence the reproduction of the workforce.

b. *Monopoly market tendency*. The international trade of exhaustible (non-produced) factors provides the trading companies (suppliers) with a higher degree of monopoly than that of the common industrial markets. The price of these factors is, in fact, given outside the competitive market law which is reflected by the normal rate of profit. Instead, it is the expression of the monopoly power over the extraction of raw materials. Hence, in the long-run, the growing demand for non-produced factors leads to a heavy dependence on energy suppliers, often foreign traders, which can lead to a profit squeeze, political tensions, and uncertainty inside the economy.

c. *Social relationships and the environment*. The antagonism between capital and labour involves environmental issues through the conflict over technical (energy) paradigms. The conservative wing is represented by the industrial corporations (as long as fossil fuels are cheap, as we will see below), while the progressive wing is represented by the environmental movements. Economic growth drives (almost endogenously) the increase of social and ecological cost that the normal prices, driven by the profit-maximizing capitalist competition and production, do not consider. This cost is represented by the natural and human damage deriving from the repercussions of capital accumulation on the environment and the exhaustion of natural resources, both of which undermine standards of living. This can lead, in the long-period, to a social rejection of the impact of pollutive production processes.

d. *Justifications for ecological economic policies*. The main reason for ecological policy is the conservation of the environment for the maintenance of living standards. As we have seen, however, the government's effort to promote the low-carbon energy transition and, more in general, ecological economic policies, can have beneficial effects for market competition by reducing monopoly rents[12] and for producers and consumers by preventing the diminishing returns driven by environmental damages. Furthermore, self-sufficiency from monopoly powers can also be an expedient to avoid the intensification of international tensions or conflicts over raw materials and foreign markets, which must be one of the primary interests of a community. We see, therefore, a multiple justification for

[12] The consideration is valid unless, as the aforementioned CER study warns, the raw materials necessary for the energy transition are traded by a lower number of competitors than those of the market of exhaustible resources.

government interventions on the relationship between environmental issues and the political economy: 1) justice on the standards of living, 2) reduction of material production costs and protection of the labour force reproduction, 3) protection of profit and consumption from ecological crises, and 4) reduction of monopoly rents associated with higher self-sufficiency and peace-keeping.

4. A low-carbon switching of techniques

Ricardo, like Smith, believes that the increase in factor returns is the primary cause of economic development and is, therefore, the main operator of a countertendency for the stationary state. Technical improvements and innovations should, in general, be stimulated by the cyclical contraction in profit caused by the fluctuation of wages. When the unit cost of labour raises above the price of new advanced machinery, capitalists begin to compete for the most profitable technique, that is, the technique that can save the most labour. The long-term tendency of the system is, therefore, to replace labour with more technically advanced machineries. Centuries after the Classical economists, this insight is elaborated by Piero Sraffa's (1960) analysis of relative prices and income distribution, which tackles the problem of the choice of techniques by comparing the possible profit rates associated with different technical paradigms for a given wage.[13] We can extend this concept to the production of commodities by means of natural and exhaustible resources by considering the latter as non-produced factors of production.[14]

To include a non-produced factor (i.e., imported oil or natural gas) within the model, we slightly modify it from the production side. We call $q = Q/x$ the physical quantity of energy material required to produce one unit of output, so that $e = q(1-a)^{-1}$ can be defined with a vertically integrated energy coefficient or embodied energy, expressing the quantity of non-produced primary factor required per unit of surplus. This is equivalent to extending the technology available in the economy with (v, k, e), which now includes the non-produced energy factor with fixed supply.

We can now analyse the institutional conditions that must be satisfied to make the energy transition economically significant. In this case, we face the problem of the choice of techniques. This can be done by comparing a traditional production process β, which uses only non-renewable resources (such as fossil fuels) to meet its energy needs, with a more sustainable process α, which differentiates the energy requirements between fossil fuels and renewable resources (such as solar energy) to reduce some energy costs while lowering the environmental impact of the production process. The hypotheses that we include in our scheme are the following: (a) the ecological technique requires a lower quantity of non-produced factor ($e_\alpha < e_\beta$), (b) the α paradigm increases the material requirements ($k_\alpha > k_\beta$), and (c) the problem of the choice of techniques does not depend on labour requirements, since it is assumed that both paradigms have the same labour coefficient ($v_\alpha = v_\beta$); therefore, we can consider the wage rate as given ($w = \bar{w}$). These further hypotheses are equivalent to saying that the ecological paradigm is *energy saving* and *capital using*, while the traditional paradigm

[13] On the switching of techniques, see also Pasinetti (1977, ch. 6), Kurz and Salvadori (1995, ch. 5) and Bellino (2021, ch. 9).

[14] The treatment of non-produced factors (exhaustible resources) without land-limitation inside a structural model of growth and distribution is an elaboration based on Kurz and Salvadori (1995, ch. 12); and Foley et al. (2019, ch. 14). On this, also consult Ravagnani (2008), Martins (2016), Kemp-Benedict (2014) and Schefold (1985).

is *energy using* and *capital saving*. The transition from fossil fuels to renewable resources is, inside this framework, what is known as the Marx-biased technical progress but refers to a generic non-produced energy factor instead of labour.

In capitalist economies, one technique is always preferred to another because of the different profitability for a given wage or price of the non-produced factor. Since oil is a productive resource, economically significant (for the hypothesis b) and with a fixed real supply, it can impose a price on the market that we assume to be exogenous, because it will depend on the investment decisions and the technique of extraction used by the traders.[15] Calling p_e the relative price of imported oil (or a generic non-produced factor), the profit rates of the two energy paradigms are the following:

$$\pi_\alpha = \frac{1 - (\bar{w}v + p_e e_\alpha)}{k_\alpha} \tag{17}$$

and

$$\pi_\beta = \frac{1 - (\bar{w}v + p_e e_\beta)}{k_\beta} \tag{18}$$

We can now calculate the threshold price of oil $\overline{p_e}$, that is, the price that, if realized, makes the choice of techniques indifferent to the decisions of the capitalists, because it is associated with the same rate of profit in both energy paradigms. By setting $\pi_\alpha = \pi_\beta$, we obtain:

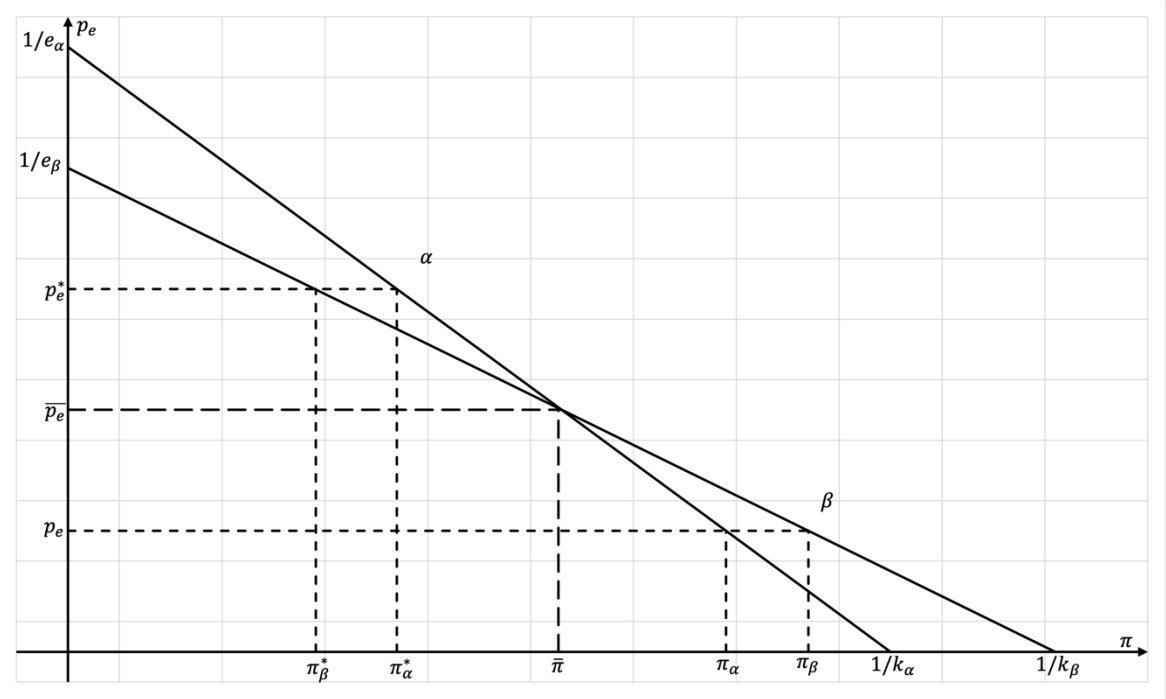
$$\overline{p_e} = \frac{(k_\alpha - k_\beta)(1 - \bar{w}v)}{k_\alpha e_\beta - k_\beta e_\alpha} \tag{19}$$

which depends entirely on the difference between the respective properties of the two techniques to save the exhaustible resource and the means of production.

As can be seen in figure 3, if firms are expected to be biased towards adopting the technique (in our case, the energy paradigm) that maximizes their profits (minimizes production costs), then for any relative price of fossil fuels that is lower than the threshold level ($p_e < \overline{p_e}$) the β paradigm will be preferred to the ecological one, even if more pollutive and exposed to supply shrinkages, because it is associated with a higher profit rate than the ecological choice ($\pi_\alpha < \pi_\beta$). Therefore, the price of the exhaustible resource must be above the threshold ($p_e > \overline{p_e}$) when the ecological paradigm has to be economically meaningful, in addition to being desirable for the environment. Only in these cases would it be more convenient for corporations to accept the higher capital requirements of the α paradigm and, encouraged by the extra-profit ($\pi_\alpha^* > \pi_\beta^*$) that is achievable, given the high price of fossil fuels, to switch from the traditional to the ecological technique, conciliating the preservation of the environment with a market economy.

[15] Furthermore, the price shall reflect the monopoly position of the trader. Indeed, Roncaglia (2015) points out that, in this context, one cannot include oil among the naturally scarce commodities strictly speaking, but rather we can talk about economic scarcity, which is dependent on the long-period degree of extraction. For a broader discussion on the formation of monopoly price of exhaustible resources, consult Ravagnani (2008).

Figure 3 – *A switching of techniques*



In what cases can we expect the price of fossil fuels to rise above the threshold? The price of a natural and exhaustible resource can increase due to a reduction in its real supply, that is, due to a reduction of its extraction or to a rapid increase in its demand relative to its reproduction rate.[16] Alternatively, if we assume the existence of a State, the government can intervene on the price of factors and indirectly encourage the low-carbon energy transition. The most common area of intervention is that of applying a tax on the consumption of non-renewable resources. This would cause the price of fossil fuels to rise above the threshold and, consequently, lower the rate of profit associated with the traditional and pollutive paradigm. The policy-makers could therefore examine the range of prices for energy material that, once realized, allow the system to self-replace and expand while progressively switching to the ecologically sustainable technique. A tax on consumption of exhaustible resources should express the social and ecological cost of economic growth in determining the prices of production. As discussed in the previous section, multiple economic and social interests are involved in promoting the ecological change of the energy paradigm. In this way, the government can privatize the social and ecological cost of production resulting from pollutive production processes, encouraging and accelerating the transition to more sustainable techniques.

The discussion conducted up to this point can lead to a broader reflection that is worth mentioning. The very facts that economic growth causes the progressive deterioration of natural resources, and that one technique is preferred over the other on the basis of its associated profitability, imply that the accumulation of capital and the choice of technique are the result of relationships that belong to the institutional level of the analysis, i.e., that of the

[16] The mechanism would be equivalent to the wage curve expressed by equation (11).

distribution of the surplus and the composition of output. Hence, the political nature of the energy transition raises the question of whether it can be sustainable or, rather, compatible with the very functioning of a monetary market economy based on the accumulation of profit.[17]

5. Concluding remarks

This contribution is intended to broaden the point of view of heterodox approaches to ecological macroeconomics towards the Ricardian and Sraffian landscapes. Depletion of material resources and ecological crises are considered the consequences of industrial production processes that exploit natural resources and damage the ecosystem, leading to incremental production costs in the primary sector and, for the society as a whole, a lowering of the standard of living. Furthermore, the exploitation of exhaustible resources leads to the concentration of power and the increase of monopoly rents. A weak self-sufficiency in the procurement of raw materials can have negative consequences in the long run, as it exposes the society to international tensions and conflicts over the ownership of exhaustible resources (historically, mines and land; in modern economies, oil and gas fields) or, more simply, to financial unbalances due to imported material inflation and external constraint. For these reasons, we can certainly count these crises among the reasons for which a government intervention can be justified.

Conservation of the environment, together with improvements or innovations in the primary sector technical paradigm, is necessary to prevent diminishing returns and the depletion of natural resources. However, in capitalist economies, the technical and institutional constraints for the energy transition are manifold. An ecological paradigm must, in fact, reach the same economic requirements as the prevailing (pollutive) paradigm that currently satisfies the basket of energy needs, that is, it cannot affect the profitability of production processes. This can take the social conflict between labour and capital towards the sphere of technology, which emerges between the efficiency of the production process and its environmental sustainability.

In the light of the discussion, we can conclude that the objective of economic policy can be considered threefold. It can act with a social purpose, to ensure higher living standards through the preservation of the environment, the transition to sustainable production techniques, the prevention of health crises, and the lowering of the cost of primary goods. It can also act with a pure market orientation: on the one hand, it can preserve free competition within the energy materials market and thus decrease the dependence on energy imports from foreign monopolies and, on the other hand, it can prevent cost increases of production. Finally, at the national and world levels, the State should be oriented towards the self-sufficiency of politically unstable countries, which could also be a useful tool for preserving a peaceful economic environment.

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[17] Cf. Martins (2016), Bellofiore (2021) and Pirgmaier (2021).

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