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The aspirations of the green industrial revolution: a historical perspective

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GREEN TECHNOLOGY FOR A NEW WAVE OF GROWTH?

The concept of green growth emphasizes the fact that environmental protection is compatible with economic growth and can even enhance it. This concept brings together a diverse set of benefits: avoiding the economic cost of environmental degradation, green comparative advantage, green Keynesian stimulus, etc. Recently, green growth has been associated with the strong belief that green technology may be able to trigger a new "wave" of productivity gains, and thus growth, comparable or superior to that generated by the steam engine, the railways or electricity. What are the main drivers that sustain this hope of a "green industrial revolution"? How can we analyse this concept in the historical perspective of technological breakthroughs and of economic growth?

THE TRANSFORMATIONAL ROLE OF TECHNOLOGY

The history of the industrial revolution and economic growth is much richer than that of technology: it is accompanied by drastic changes in the organisation of work and business, of social compromise, or of consumers' behaviour. We nevertheless focus here solely on the role of technologies, by putting forward the key characteristics of those that have shaped history. Beyond the ability of such technologies to reach large and diverse sectors, we highlight the way in which they were able to open doors to profound economic reorganisations with great productivity potential. They did not merely allow business as usual at a lower cost, but they enabled things to be done in a completely different way.

THE LIMITS OF GREEN TECHNOLOGY

One may doubt the ability of the currently envisaged green technologies, which are at the intersection of energy and climate issues, to pave the way for such reorganisations. Green electricity remains electricity, while the green car remains a car. Economic organisation is certainly likely to change, especially under the influence of information and communication technology, but while new energy technologies must be thought of in this context of transformation, it is difficult today to see how they can play a leading role. The hope for a green industrial revolution and a new wave of growth is then based on technological breakthroughs and innovations of a different nature, such as the functionality economy.

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1. INTRODUCTION

While local and global environmental challenges are continuing to grow, many industrialized countries have been facing lower productivity gains since the end of the period of high growth in the 1950s and 1960s, along with a serious economic crisis in recent years. In this context, many advocates of an increase in environmental protection emphasize the positive economic effects of the measures they propose. Proponents of this view often cite the fact that action is required to avoid very serious economic impacts from environmental degradation (e.g. Stern, 2007; TEEB, 2010). However, the heart of their argument has changed. For example, they put emphasis from 2008 on the growth stimulus effect of investments in green technologies and infrastructure (see for instance Robins *et al.*, 2009). In addition to this green Keynesianism, proponents of green growth insist that the measures in favour of the environment are opportunities to make our tax system more efficient through environmental taxes or to stop the wastage of certain resources (Jacobs, 2012).

Other authors such as Jeremy Rifkin (2012) and Nicholas Stern (2012) go even further and predict a new industrial revolution with a strong ecological content, based on green technology, and which we refer to herein as the "green industrial revolution" (GIR). Making reference to the history of the industrial revolution in the nineteenth and twentieth centuries, these authors, along with others with similar outlooks, raise hopes—voluntarily or not—for a burst of economic activity that will last for several decades and will generate a new wave of productivity gains and therefore growth, which will be "comparable, or superior, to those generated by the introduction of the steam engine, railways, electricity or information technology" (Stern, 2012).[1] The promise of the GIR is not to protect the economy and its growth potential from resource scarcity and environmental degradation, but to trigger a new wave of growth that will get industrialized countries out of their current low growth situation. Under what conditions would this new wave of green growth be credible? Is the GIR anything other than a positive and inspiring story, which focuses on opportunities rather than on the dangers of environmental degradation?

We have addressed this question through the adoption of a historical perspective,[2] an approach motivated by the fact that GIR proponents directly

1. The concept of technological revolution is at the heart of the Schumpeterian tradition to explain the long economic cycles. Can we easily link, historically, the technological cycle and the economic cycle? As recognised by all authors, for a great invention to spread and to have a significant macroeconomic impact, many reorganisations are necessary. Thus, electricity had to wait a long time before leaving its luxury "niche" in the department stores and entering into factories, and it is only when the organization of work in factories was modified and when workers were suitably trained, that companies were able to derive substantial economic benefits. But this primarily concerned a few pioneering companies, and it took decades before these practices became widespread. It is then empirically extremely difficult, if not impossible, to make a link between the invention of electricity and the macroeconomic development of a country. The exercise is even more difficult when one looks not at one invention but at a constellation of new technologies, and when one tries to link such technologies with a wave of growth. The empirical basis of the Schumpeterian school of thought is therefore fragile.
2. Our approach differs on this point from many studies, for example including those contained in the special issue of *Energy Policy*, Volume 50, 2012, which used history to study not the growth potential of green technologies but the conditions and barriers to the diffusion of green technologies and more generally to the transition to a low carbon society.

or indirectly invoke history[3] to support their narrative of a new wave of growth driven by green technology. Furthermore, while history never repeats itself in an identical manner, it may be possible to identify the processes that led new technologies and more generally innovations to sustain cumulative growth, and detect today whether the same processes are on-going.

Section 2 identifies the characteristics of technologies that marked the industrial revolutions of the past two centuries by enabling large gains in productivity; while section 3 analyses whether green technologies fit this profile or not. Section 4 focuses on a central feature: the ability of these technologies to enable "indirect" productivity gains or to permit major "reorganisations" of the economy and of societies. Section 5 examines the reorganisations which—regardless of green technologies—may mark the transition towards greater environmental sustainability.

As GIR advocates, we focus here on environmental issues at the interface of energy and climate.[4] In referring to "green technologies" we therefore mean those related to the production and consumption of energy and those that offer alternatives to fossil fuels. We also delimit the scope of this analysis by restricting ourselves to technologies that are now at centre stage and that make up the heart of green investment, starting with renewable energy—solar and wind, primarily—carbon capture and storage (CCS), electric vehicles, etc. In doing so, we exclude technological breakthroughs from this discussion, a matter that we return to in the conclusion.[5]

2. PROFILES OF TECHNOLOGIES THAT HAVE LEFT THEIR MARK ON THE HISTORY OF INDUSTRIAL REVOLUTIONS

The history of the industrial revolution and economic growth is much richer than that of technology: it is accompanied by drastic changes in the organisation of work and business, of social compromise, or of consumers' behaviour. Like GIR promoters, we nevertheless focus here solely on the role of technologies. Can green technologies induce productivity gains comparable to the mechanization of the textile industry or to the dissemination of innovations such as the steam engine, electricity, the steel industry, the combustion engine, synthetic chemistry, telegraphy or telephony? In this section we try to identify some characteristics that are common to these developments.

2.1. Productivity gains

Firstly, although fairly evident, it is worth remembering that the great innovations of the past have led to increased productivity, i.e. to the provision of goods or services at a much lower cost than previously possible through other techniques. The fundamental innovation at the origin of such advances was not necessarily intended to deliver the eventual outcome (the examples of the transistor and the laser are emblematic in this regard). At its "beginnings", a new technology may rely on non-cost benefits to create a niche market, such as electric lighting, which was readily taken up by high-end department stores due to the luxurious image it conveyed. But a technology must gradually generate significant productivity gains if it is to extend beyond its niche and have a lasting impact on its areas of application.

How do technologies that influence economic history generate their productivity gains? This can be in a fairly simple and direct way, such as for example the mechanization of the textile industry that increased worker productivity within a few decades and brought down the price of yarn and fabrics. Synthetic chemistry provides another example of this type of influence; it has developed by providing the textile industry with substitutes for natural dyes that are often scarce and subject to speculation, such as indigo from India.

In addition, the "major technologies" have, more indirectly, opened the door to profound economic reorganisation. The steam engine for example, through the substitution of hydropower derived from water courses, not (only) provided a cheaper energy source, it also made possible the geographical concentration of factories—previously it would not have been possible to group together several mills onto the same site—and allowed them to be located nearer to primary resources and/or to places of consumption. The advent of electricity meant that the

3. Directly in the case of Rifkin and indirectly for Stern, who refers to the work of Carlota Perez (2002) on the links between technological revolutions and industrial revolutions.

4. Technologies of recycling, of the protection of natural capital (the depollution of water and soil, for example) and technologies in the field of agriculture are beyond the scope of this paper, but strictly speaking they should be included in any analysis that seeks to estimate the potential economic impact of long-term green technology.

5. Note that Stern (2012), and Rifkin (2012) even more so, rely—especially—on green technologies that are already available to promote the GIR.

link between the energy source and industrial locations could be extended even further,[6] and the electric motor opened the door to a spatial reorganisation within factories towards greater rationality.[7]

Finally, as regards "reorganisation", we must not forget to mention the role of network technologies, i.e. technologies to transport goods or information: vehicles and roads, trains and railways, telegraph, telephone and now the new tools of information and communications technology (ICT). Railways have enabled the expansion of markets, the exploitation of economies of scale and comparative advantage, specialization of territories, etc. Similarly, information and communications technologies, new or not, have facilitated international trade, just-in-time production, coordination within networked companies and of very large companies.

Reorganisations are not always deep, and the border between "direct" and "indirect" productivity gains is very indistinct.[8] But it should be noted that the technologies that have made history have not only lowered the price of certain goods or services, but have also—often—opened the door to economic reorganisations that have generated significant productivity gains.

2.2. The potential market

The technologies that have shaped history have had an impact in the major sectors of final or intermediate consumption. Let us start by focusing on final consumption and the example of textile mechanization. Fabric, for clothing and furniture, was traditionally an important part of most household budgets, typically constituting the second highest sector of expenditure after food with a share of 12% to 16% throughout the nineteenth century (Verley, 1997). The decline in the price[9] of fabrics, a product with a high price elasticity of demand, has consistently expanded the market for this product in terms of volume – socially and spatially across the world. It was only later that a tendency towards market saturation became apparent. The first industrialization was led by textiles, which accounted for about one third of industrial production. Thus, there was great demand for fabrics in the sense that it was an important proportion of the final consumption expenditure at the time, and also because the "potential" demand was significant.

Obviously, a consumption sector can—unlike textile at the time—represent a small share of household expenditure and yet be the engine of an "industrial revolution". As noted by Ernst Engel, after food or clothing, there are "superior" needs that increase with income such as furniture, leisure, culture, health and mobility. The railway and automotive industries stimulated, or even created, their own market, showing new forms of need that contemporaries had not initially considered. The promoters of railways expected to greatly reduce the cost of transporting goods and therefore stimulate trade; they had no idea that the demand for travel would grow exponentially. For example, in the early nineteenth century, a French Minister, Adolphe Thiers, joked about the influx of Parisians wanting to make the train journey between Paris and Saint Germain, declaring it to be a toy that Parisians would quickly tire of.[10]

So far we have focused on the final consumption sector, that of households. But the key technologies in economic history have also impacted on intermediate consumption. In this category belong the steam engine, the train, synthetic chemistry, metallurgy, electricity and ICT. All these technologies have had wide-ranging impacts across many sectors, if not all of them, to varying degrees. Many authors have emphasized the importance of the generic nature of these technological innovations (Pearson and Foxon, 2012). Transport networks of goods and information concern all sectors.

6. Transportation of coal was only economically profitable by sea or inland waterway. Therefore coal could only be used in close proximity to ports and waterways. Electricity, however, could be distributed more widely, although it did not take off until advances had been made in high voltage transport and in network construction, which were originally regional.
7. A factory can then be organised to reduce the transport of materials as much as possible (e.g. in steel mills) or to adopt the assembly line method (moving the product, rather than the workers) which already existed in an embryonic form, in particular for car bodywork.
8. Thus, the steam engine has enabled the avoidance of some of the problems associated with hydropower, such as flow irregularity, the drying up of rivers in summer in southern regions, and the freezing of water courses in winter in northern regions, along with the disadvantages of sailboats, such as irregular schedules and transit times. It is not easy to categorise these benefits of the steam engine into "direct" or "indirect" gains.
9. Note that productivity gains do not automatically translate into lower prices, as producers may adopt different strategies, such as in the perfume and other luxury goods sectors.
10. The Paris-Saint Germain train, or the St. Petersburg-Tsarskoye Selo, were not built to allow Parisians, or Petersburgians, to visit the countryside, but rather to demonstrate to political and financial decision-makers the feasibility of railways in order to build lines that spanned whole countries.
NB: to meet these "new" needs, productivity gains towards their production are certainly necessary, but so also are gains generated elsewhere in the economy and that stimulate an additional demand for these needs.

The steam engine, which was first applied in the coalmines, went on to revolutionize transport and became integrated into factories.

In summary, while their non-cost benefits enabled them to develop initially in specific niches, technologies that have had an impact on history have mainly spread through the generation of significant productivity gains, directly or indirectly. They have touched upon major sectors of consumption or have spread to the whole economy. Finally, we must note the existence of a third characteristic, the "dynamics of creativity", that is beyond the scope of this paper. For example, the textile industry has driven quantitative development but also—it is important to stress—the qualitative improvement of the construction of machinery and the chemical industry. Innovations in textiles have driven advances in upstream sectors such as mechanical engineering, the inorganic chemistry of whitening products and the chemistry of synthetic dyes in the second half of the twentieth century.

3. COMPARING GREEN TECHNOLOGIES TO THE MAJOR INNOVATIONS OF YESTERDAY

Do green technologies correspond to the same "profile" as the major innovations that have marked economic history and generated significant productivity gains? Let us begin by discussing the size of the potential market.

3.1. The potential market for green technologies

The market for green technologies is booming. The market for renewable energy reached $260 billion in 2011 (Bloomberg, 2012), twice as much as in 2007. Admittedly, this represents only 15% to 30% of investments in the energy market,[11] and between 0.5% and 2.5% of total investments. However, the aforementioned technological revolutions were initially related to consumption niches and segments of industry, traditional technologies and sectors remaining dominant over a long period in quantitative terms. In the infancy of the steam engine, its low energy productivity and the pumping nature of its movement (rather than a rotary movement) restricted its use to the removal of water from coalmines. Around eight decades elapsed between Newcomen's patents (1710-1712) and the steam engine's escape from this economical "niche".[12] It is therefore difficult to draw conclusions from the size of the current market for green technologies. But what can we say about their potential market?

From the perspective of intermediate consumption, green technologies can be considered as generic. All sectors consume energy for their heating or mobility needs, and some more than others, such as transport, agriculture and manufacturing. In terms of final consumption, energy costs represent more than 8% of French household budgets (Merceron *et al.*, 2010). Finally, in macroeconomic terms, energy costs in the United States are of the order of 8% of GDP, with levels of around 10% or greater during oil peaks (EIA).

The size of the potential market for green technologies is therefore substantial—comparable to the fabric throughout the nineteenth century—and the outlook is anything but bleak. Whether countries decouple their energy consumption and their GDP or not, in relative or absolute terms, it is a safe bet that our societies will continue to need "energy services" at least as much as they do today. Whether the heating of houses becomes more ecological, or is replaced by improved isolation and automation, there remains a large market for green technologies.[13]

Finally, it should be noted that according to authors within the ecological economics movement, the role of energy in the functioning of the economy is underestimated (e.g. Ayres and Warr, 2009). They emphasize that "living standards" and energy consumption are closely linked: without energy, there is no food, no mobility, no heating, no industrial processing, no computers... We can compare this observation to the work of certain historians that consider energy to be at the heart of industrial revolutions. Thus, for R.J. Forbes (1958), the invention of the steam engine in the eighteenth century is the central feature of the industrial revolution, followed by the introduction of new driving forces: the hydraulic turbine, the combustion engine and the steam turbine in the nineteenth century, followed by the gas turbine in the twentieth. For Wrigley (1988), it is the emergence of

11. According to GEA (2012), Chapter 6, investments in energy supply and demand are in the range of 900-1500 billion dollars. And the share of investment in the energy sector is of the order of 4% to 8% of global investment.

12. The French steel industry in the mid-nineteenth century was not more important than the Parisian furniture or clothing industries; while the automotive sector did not amount to much prior to 1914, and nor did the production of computers in the 1980s.

13. To be precise, it is the large market of green technologies and "services" that will always develop. The former can be reduced in favour of the latter (craftsmen that insulate buildings, rental vehicles in car sharing, etc.).

energy sources and raw materials independent from land production the mineral-based energy economy, which is at the heart of the industrial revolution. While these works do not receive unanimous acceptance among historians, no more than those of Ecological Economics receive from economists, we can however draw from this analysis the conclusion that green technologies seem to fulfil the criterion of "market size", making it a potential successor to the steam engine.

3.2. "Direct" productivity gains

In addition, it remains necessary, however, for green technology to be able to generate productivity gains. Let us start with the direct gains, which in this case are the costs of energy production based on renewable sources or CCS, or the cost of electric vehicles. It is obviously very difficult to make projections of the costs of green technologies over ten, twenty or thirty years. However, given the present state of knowledge and by limiting ourselves to technologies that are at the heart of energy transition today, we must be cautious.

CCS does not reduce the cost of fossil fuels, but in fact the opposite. The cost of nuclear power—if it can be classified as a green technology—is widely discussed, but it must be noted that the current trend is towards its increase. On the contrary, the costs of renewable energies and electric vehicles are decreasing, and some hope that the renewable mix will be competitive in the short or medium-terms compared to fossil fuels and conventional internal combustion engines, even when taking into account the necessary changes to various networks. However, even for green tech promoters (e.g. Fraunhofer, 2012), it is difficult to imagine a drastic drop in the price of energy or mobility compared to the current situation. In future, energy is likely to become more expensive rather than the opposite. Surely, energy-saving technologies would be able to soften or even counteract this trend. But the role of energy transition and in this case of green technologies seems to be to protect the global economy from oil shocks rather than to drive down the price of energy services.

If we limit ourselves to green technologies that are already available and growing, we can therefore be sceptical about the potential of growth through "direct" productivity gains. Can they induce a profound reorganisation of the economy?

4. MUST WE BE DETERMINISTIC IN ORDER TO BE OPTIMISTIC?

Green technologies can profoundly transform the way energy is produced. Instead of a centralized energy system, we can imagine one that is completely decentralized, where every consumer and every industrial site is a producer of energy. The question we ask here is whether green technologies can induce deeper reorganisations in the consumers sectors and the rest of the economy, as did the steam engine, electricity and transport networks.

Stern (2012) is not explicit on this point. The heart of his analysis is based on the addition of green technologies to the current technological revolution identified by Perez (2002). The latter, in the Schumpeterian tradition, considers the emergence of a new wave of growth thanks to a new technological "constellation" which strongly "interacts" with the organization of the economy. But her new constellation is based primarily on ICT. Green growth is a direction for the deployment of the information revolution; it is not a revolution in itself.[14]

J. Rifkin underlines the importance of ICT and renewable energy, given that previous industrial revolutions, according to him, were combinations of revolutions in communications along with energy revolutions.[15] He displays a strong technological determinism, making the assumption that energy technology determines not only the organization of consumer sectors, but more generally the economy and society. As fossil fuels are centralized, they would have led to major vertical businesses and to the Taylorisation of factories as well as schools. As he sees renewable energies as decentralized, they would then lead to a distributed, lateralized economy.

There is a great temptation to regard the nineteenth century phenomenon of the concentration of workers into factories on a growing scale and on an increasingly hierarchical basis, as the logical consequence of mechanization and the use of "centralized" energy sources, such as large steam engines. It is indeed machinery and concentration that have been the most striking impacts experienced by the people that lived through the beginning of the industrial revolution. Yet the process of concentration has very different origins, starting

14. Personal communication with the author.

15. However, he seems to give energy the leading role, stating that: "energy regimes shape the nature of civilizations", the way they are organised, they distribute the fruits of economic activity and trade, or the way political power is exercised and social relations structured.

with the willingness of entrepreneurs to specialize and, in particular, to have better control over their workers (to monitor the quality of work, to have control over working time, for the protection of trade secrets, etc.). Decentralized proto-industry had already started to decline before the steam engine began to transform industry. While concentration continued after the adoption of an energy vector such as electricity, even though it carried the promise of the revitalization of trades and home production in rural areas—which were in decline but regarded with nostalgia since they helped to ensure social order.[16]

Historically, technological developments have been accompanied by a substantial reorganisation of the economy and society. The existence and direction of causal links, and whether their characteristics were unique and mechanical or imprecise and conditional, is a debate that divides the community of historians. Unlike Rifkin, our analysis is that technologies do not determine the organization of the economy, but open doors to its reorganisation. The choice of path to be taken is as much a matter of political and economic power relations. By "opening doors" technology is not neutral. While no one is forced to enter through an open door, it is however very attractive. And it is not clear whether we can ever go back.

Without prejudging the future outcome of such power relations, we ask the question: which doors do green technologies open? Without starting from the assumption that the economy is organised according to its energy system, through which process can green technologies influence consumers and other sectors of the economy?

Following the logic of J. Rifkin, let us imagine a completely different organization of energy production, with a boom in the development of renewables and the domination of electrically powered vehicles. Electricity would no longer be produced in large power plants, each building would be a source of energy, and the use of a smart grid would facilitate electricity exchanges, including with electric vehicles. This decentralized scenario is possible, as is a centralized renewable scenario. But how does it transform the organization of the production of other goods and services in the economy? CCS, nuclear and renewable energies transform energy production, but do not provide a new energy vector. Surely the electric grid would become smarter in the context of a transition towards a system that is 100% renewable. But ultimately it is always about a "switch" that is turned on or off, in a factory or a building, as and when necessary. Who can differentiate between an electron derived from a coal plant or one from a solar panel (Zysman *et al.*, 2012), between an electron transported by an old electric grid or one carried by a super-smart grid? What difference does it make to the consumer? Electrons may be "green" instead of "brown", but they are still electrons. The same is true for the electric car: it is a car with a different engine, which we may refer to as green, but it remains a car that will be driven on the same roads as today, and will be used in the same way. We change the engine of the "vector", in this case the car, but there is no new vector opening the door to new uses.[17]

Let us remember, therefore, that the reorganisation enabled by green technologies already seems to have been "exploited" by the twentieth century diffusion of electricity, automobiles and their respective networks. We can therefore remain sceptical about the potential indirect productivity gains of such technologies. The economic organization is certainly likely to change in the coming decades, especially with the spread of ICT that will open doors, but it is difficult to see green technology as having a leading role in this transformation.

To conclude this section, it should be noted that authors who support the GIR should be credited for raising our awareness on the interactions between green technologies and those of the "information age". Thus, lightweight and resistant nanomaterials can transform electric cars into "hypercars"(Lovins *et al.*, 2000) that are extremely lightweight and energy efficient. ICT can make our electric grids smart and thus able to exploit the full potential of decentralized renewable energy, despite the intermittency of some of these sources. "Smart meters" and other home automation tools can enhance the energy saving measures in buildings, and new materials can improve their insulation. This does not change the fact that green technologies do not seem to open the door to "indirect" productivity gains, but may provide more hope for direct gains in this broader context of innovation.

16. In fact, one rural activity that was carried out in people's homes, hosiery in the town of Troyes, was undergoing a revival, although it eventually disappeared during the 1930s crisis.

17. Strictly speaking, it should be noted that the electric car may lead to new uses because of its limited autonomy in terms of mileage. It cannot be used in the same way as a vehicle with an internal combustion engine. That said, this is a constraint and not a new freedom.

5. DO WE NEED GREEN TECHNOLOGY TO REORGANISE THE ECONOMY?

Technologies do not seem to open the door to profound reorganisations of the economy, except possibly within the energy sector. But as we have seen above, history has been marked by reorganisations that were autonomous in relation to technological developments, along the lines of the Taylorization of work. Thus, in this "exploratory" section we present a number of new economic organizations, discussed in the context of the building of a green economy.

Let's take the example of car sharing, or more generally the collective use of private cars. It should be noted that this can be achieved using electric vehicles, such as the AutoLib' in Paris, but it can also be done with conventional cars. Car sharing is only one example of what we usually call the functionality economy. The functionality economy is a new economic organization which—in a very broad definition- considers usage to be more important than ownership and favours service providers over the producers of goods. Thus, rather than buying a car—electric or not—a consumer can buy a mobility service: the right vehicle to suit a particular requirement can be accessed as needed. Rather than buying tyres, a road haulier buys a tyre service for its lorries: tyres are installed and maintained by a company who remains the owner of the tyres. Such a system can be extended to a large quantity of goods, from household appliances to photocopiers, through carpets and industrial solvents. Such a system is supposed to be resource-efficient because the goods are likely to be more durable, better maintained, repaired, recycled and/or fewer in number.

Can this "green" economic reorganisation sustain the hope of a GIR by generating major productivity gains? The current economic system leads to the production of goods that rapidly become obsolete, and to the possession of underused goods: a car costs around 6,000 euros per year, all expenses included, and spends 95% of its time in a car park. The functionality economy, by organizing the collective use of individual goods, enables the division of these costs and the realization of productivity gains that are potentially immense. "Potentially" in the sense that the macroeconomic impact of the functionality economy unfortunately remains a little-studied subject. It is true that economic growth is rarely the objective of the promoters of the functionality economy, who prefer to broaden the notion of value by incorporating environmental sustainability, territorial dynamics and the quality of work and social links.

The functionality economy is an example of green economic reorganisation. We can also mention the reorganisation of industrial sites to promote synergies between plants in terms of energy or materials, or the industrial ecology, among the reorganisations that are grouped under the term "circular economy".[18] Or another example, beyond the energy-climate field, is the development of short production chains, for example in the agricultural sector.

6. CONCLUSION

The academic literature is full of arguments in favour of compatibility between growth and the environment, which are grouped under the term "green growth". The strongest of these arguments remains that of the environmental damages that must be avoided, particularly the impact of abrupt climate change, "tipping points", or future energy shocks. Environmental protection is therefore a necessity. Can we go further and, as GIR proponents believe, hope for a real growth "wave" that lasts several decades as a result of new green technologies?

We have seen that the hope for a GIR is fragile if we consider green technologies that are at the heart of investments in energy transition. This is not that much because they concern only a small part of the economy, but it is due to the doubts over their ability to generate significant productivity gains: directly, by lowering the price of energy or mobility; or indirectly by opening the door to profound economic reorganisation.

Technologies that have shaped history have enabled such reorganisations, such as electricity, and supporters of the GIR must specify how green technologies can do the same. Surely the energy system can evolve dramatically with the emergence of renewable energy, electric vehicles and the development of smart grids, and it can shift from a centralized system to one that is completely decentralized. But how could the rest of the economy be encouraged to reorganise itself? If we do not want to give in to technological determinism, then it is clear that green technologies will not deliver an obvious "reorganisation".

To realize the hopes of a new wave of green growth, we must rely on major breakthroughs in green technologies or on green and

18. The circular economy favours the eco design of goods, their production on sites that promote synergies between industries, their distribution, recycling... and a functionality economy.

"techno-autonomous" economic reorganisations. If the expansion of knowledge is at the heart of the industrial revolution (Mokyr, 2002), then we can anticipate technological breakthroughs. These would include the development of nano-batteries, biofuel production by novel bacteria or from algae, cement that captures CO_2 and all the technologies promised by Biomimicry: why not produce hydrogen in a process that draws inspiration from photosynthetic processes in nature? Why not imitate marine sponges in their ability to build their silicon skeletons at 4°C? Such breakthroughs remain hypothetical. The functionality economy and more generally the circular economy are green reorganisations that do not necessarily imply new green technologies but still contain the potential for significant productivity gains.

However, surprises are always possible, whether technological or organisational. After all, those who lived during the previous industrial revolutions were not aware of the transformations underway and of what they would bring in terms of their standards of living. The best approach therefore is to achieve green technological and organizational transformation, to avoid environmental degradation—and its impacts, whether economic or otherwise. Whether this will lead to a new wave of growth will be left for history to decide.

The GIR is clearly a positive and inspiring story, but there is room for doubt on the ability of green technologies to stimulate a new wave of growth comparable to the industrial revolutions of the nineteenth and twentieth centuries. And we must be aware that unfulfilled aspirations can lead to major steps backwards.

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