Innovation and sustainability: a contribution to an integrated approach

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1. Introduction

More than two decades ago, Christopher Freeman wrote about the emergence of a new green techno-economic paradigm (TEP), concluding that: "It is therefore not soon to start thinking about and designing and building institutions and technologies which are likely to combine in a sixth (environmental) TEP" (Freeman, 1992: 207). In the debate which followed the MIT models of the 1970s on the limits to growth (see Meadows et al, 1972), two opposing parties were formed: the 'pessimists' (arguing for the 'zero growth') and the 'optimists' who included the SPRU and the author himself. The latter claimed that growth could and should continue into the 21st century provided two conditions were met: the implementation of a set of institutional changes favouring a different world development path; and the reorientation of the R&D system with a shift in the rate and direction of technical change to secure the first objective.

In response to increasing greenhouse effects, much progress had been made mostly due to institutional change rather than to technological change (Freeman, 1992:191). Important outcomes had been already achieved. In Freeman's view, however, a much bigger effort had to be carried out regarding the improvement and development of new technologies, ICT being a good starting point.

However, we wish to emphasize now two basic ideas: the centrality of a set of institutional changes; and the reorientation of the R&D system with a shift in the rate of direction of technical change. It is rather significant that Freeman did not emphasize radical technological innovations to underpin the transition, since his stress was on the general conditions to pave the way for the new green techno-economic paradigm.

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In fact, and in spite of a remarkable progress in new energy technologies, the transitions to sustainability as analysed by the transitions scholars do not seem to be pushed by radical technological innovations. Radical innovations (and not so radical) make them viable. Transition is analysed from the perspective of the planet and civilisation sustainability – the driving force - and has been gradually making its way via major shifts at institutional, policy and values levels (Unruh, 2000 and 2002; Van den Bergh and Kemp, 2006; Geels, 2010), resorting to ongoing technological progress.

At the present day, the role of technological innovation as a major tool rather than the driver of shift to a sustainable world seems a relevant and subtle distinction within innovation studies scholars. Maybe here too we are facing again the existence of two sides: the optimistic party and the prudent party, though both of them are determined supporters of transformative action.

The two groups could be organized according to two criteria: the role of technological innovation in the transition process; and the vision on the new world we are going to transit to.

2. The problem

Over the last years, and led by the IPCC – Intergovernmental Panel on Climate Change, a broad consensus has been formed among the public opinion and the world political leaders, according to which the current climate change – encompassing global warming and more frequent extreme climate phenomena – has an anthropogenic origin. The emission of greenhouse gases[2] – carbon dioxide, nitrous oxide and methane, mostly[3] – is the major source of these alterations.

Experts, such as Nicholas Stern, pointed out a threshold that should not be exceeded under risk of uncontrollable consequences on human habitats, fauna and flora on the planet (Stern, 2009) and eventually the survival of the civilisation, as we know it. This threshold is + 2º C of the global average temperature of pre-industrial times. Inaction might lead to an increase of about 5ºC which would create a grave disorder in climate and environment with subsequent mass migrations, global conflict and huge difficulties (Stern, 2009, p. 31).

[2] Strictly speaking, this is an increase of intensification of the natural greenhouse that surrounds the Earth and was essential to the emergence of life on Earth. Without it, the infrared radiation from the planet's surface would leak towards the outer space, leading to very low temperatures (Santos, 2012, p. 41).

[3] The main greenhouse gases include water vapour, carbon dioxide, methane, nitrous oxide and ozone. The first is of natural origin, the following four of anthropogenic and natural origin. Other gases are exclusively anthropogenic like chlorofluorocarbon, perfluorocarbons, and sulphur hexafluoride hydrofluorocarbons (Santos, 2012, pp. 40-41).

To this must be added the enormous pressure on natural resources caused by the growth of the world population and the extension of industrialisation, urbanisation and motorisation, and the resulting decline of vital resources like water, arable soils, the fishing grounds, the quality of the air, etc., not to mention the depletion of conventional deposits of oil and natural gas, and various ores whose extraction faces steeply decreasing marginal returns. The degradation of resources is another problem and results from various effects such as the emission of waste pollutants that affect the sustainability of soils, life in the sea and in rivers and groundwater.

Despite the progresses observed, mostly in the EU, the targets to be met are still overwhelming. The long run objective in the EU is: "to deal with climate change and to achieve our target of reducing EU greenhouse gas emissions by 80 to 95% by 2050" (EC, 2011, p.2). Reducing drastically greenhouse gas (GHG) emissions, increasing recycling, saving ores and raw materials require huge and rapid economic and societal transformations.

Technological progress has offered increasingly efficient solutions, like wind and solar PV energy, which albeit extensively used in some countries, have managed to replace conventional sources quite partially. This is due to multiple reasons: insufficiency of existing technological solutions, existence of powerful socio-technical systems carbon-dependent which are hindering the transition (Unruh, 2000; Geels, 2004), a biased price system and the complexity of the institutional and political transformations required.

After carrying out an analysis of twenty scenarios for GHG emissions on the horizon of 2050, most of which quantitative and 11 global[4], Söderholm et al. (2011) drew two major conclusions: firstly, most scenarios ignore, or seriously overlook institutional and political issues, crucial to achieve "transformations at an unprecedented scale" (Söderholm et al., 2011, p.1113); secondly, "the development and introduction of carbon-neutral technologies is key for achieving a low-carbon future" (Idem, p.1113).

The authors suggest a co-evolutionary approach to manage the transition, combining the technological change and systems innovation with the institutional theory and the literature on governance (Ibid, p. 1113). This perspective is interesting since it originates in the foresight studies, on which is based the policy formulation, namely in the EU, while including a strong concern with the creation of new energy technologies.

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[4] The first quantitative global scenario presented is from the European Commission, *World Energy Outlook – 2050* (EC, 2006).

3. Analytical tools

The economics of innovation has provided very relevant analytical tools to address the sustainability issue. We refer to the concepts of technological trajectory, lock-in and path dependence, and, finally, techno-economic paradigms.

The direction of technological innovation

Briefly, we may characterise the dominant technological innovation trajectory in the business sector (including organisational innovation) over the 20th century in Europe and the United States – until the advent of the flexible production systems, which altered some of these aspects – by features such as:

- Replacement of labour with machines;
- Intensive use of cheap abundant energy;
- Standardisation of components, processes and equipments;
- Exploitation of increasing economies of scale;
- Planned obsolescence of products, both through the acceleration of physical wearing out and the powerful effect of marketing, particularly on the consumer goods markets.

To achieve sustainable economic growth, it is necessary to shift this dominant direction towards energy and materials saving, with more efficient solutions, with less pressure on consumption, with an increase in recycling, and imaginative solutions for renewing consumer goods.

In conventional economic models, this result is achieved through the stimulus of prices. According to them, at a time when the price of energy is too high, the economic agents will tend to choose more efficient equipment and processes, either firms or households and individuals. A serious problem derives from the existence of a distorted price system, where prices do not reflect neither social costs (externalities like GHG emissions and environmental damages in general) nor long-run depletion of limited natural resources. A compelling example is the strong fluctuation of fossil fuels prices led by short-term demand, speculative investment and divestment and politically run global cartels.

In this line, we could envisage to speed up this process by creating more taxes on energy consumption. However, there are several problems with this argument. The first is that politically this kind of green taxation may not be easy, or even feasible, in democratic societies, beyond a certain level. The second is that it tends to increase inequality, because its relative incidence is more severe in the poorest, as it turns out in many countries with regard for example the access to heating of dwellings in the cold season. The third is that this process may not be fast enough to deal with the urgency of the problem.

It is up to the State to intervene through stimulus policies to new energy technologies, the launching of research programs in this area (Mowery, Nelson and Martin, 2010) and the imposing of strict regulations in fields like recycling, for example. This has been followed by the European Union since the mid-1990 – due to the need to comply with the Kyoto goals[5] -, and enhanced with the adoption of the energy and sustainability policy in 2007.

This style of policy is a mix of Keynesianism – large environmentally-friendly infrastructures programs –, with infant industries protection – through the allocation of subsidies for the production of electricity with technologies that are not yet competitive -, and with the encouragement of research in the areas of relevant knowledge. It needs ample public support because it represents a considerable financial effort in times of budgetary constraints in most European countries and beyond.

However, there are a large number of historical precedents. Mariana Mazzucato argues that virtually all relevant generic technologies (*general purpose technologies*) in the 20th century were driven, financed and often directly promoted by the government and developed in public laboratories: the radar, the computer, nuclear energy, information technologies, the Internet and the world wide web, to which we should add the sequencing of the human genome, cloning techniques and virtually every scientific advance relevant to the development of biotechnology and nanotechnology (Mazzucato, 2014).

Lock-in and path dependence

A second aspect is that of lock-in and path dependence, which appear interrelated. These concepts originate from studies, in an evolutionary perspective, on the adoption of new technologies by Paul David and Brian Arthur, more precisely in the case of the choice between competing technologies. As David demonstrated in a study that became a classic of technological diffusion (David, 1985), that the adoption of a new technology can be decisively influenced by factors unrelated to its efficiency and cost, in cases that involve strong network economies and high learning costs, which tend to favour the preservation of the status quo (see

[5]The Kyoto Protocol of 1997, which the European Union has ratified, imposed a set of binding targets, particularly with regard to the reduction of GHG emissions to be achieved until 2012.

also Arthur, 1989). There is thus a deadlock or *lock-in*, in the transition from a technology to a more advanced one. This phenomenon can be interpreted as a case of path dependency (David, 1994; Arthur, 1994). The occurrence of this phenomenon on the scale of large socio-technical systems (Unruh, 2000), as for example the energy system, combined with the inertia of institutions and policies and the power of vested interests, may hinder or prevent the transition to another model or paradigm.

Techno-economic paradigm and paradigm shift

In the economics of innovation, there is a dominant idea that ruptures (or revolutions) in the technological development of societies periodically operate, associated with the extensive application of radical innovations. These do not occur in isolation, but rather they are linked in a coherent and interrelated system. At a given moment, technologies develop in association with each other, combining and generating externalities which "strongly favour the generalisation of a particular type of equipment and the corresponding organisational model, while discouraging other kinds" (Perez, 1988, p.86). We are, therefore, in the presence of "technological systems", in which the Schumpeterian inspiration is evident, but now being specifically highlighted the economic and institutional aspects.

As to the first, Perez wrote that, in each successive revolution, a profound transformation of the "common sense" not only of engineers but also of managers and investors takes place, and a new, more productive and more profitable, ideal model of practice is created (a new *best practice*). Perez called these models techno-economic paradigms (Perez, 1988, pp.86-87). The unifying element that conveys the new paradigm in the awareness of economic agents is the emergence of a productive input for general purposes, with such a low and declining price that produces a huge impact on the cost structure. The new key inputs, whose prices tend to decrease rapidly due to the combined effects of advances in technology, economies of scale and learning economies, have a big applicability and enormous impact. They are able to give rise to sectors, which are themselves in turbulence, and to transform the various sectors and economic spheres of society. At the turn of the 19th century, they were the heavy electric industry, chemistry and mechanics; in the post-World War II boom, the oil, plastics, petrochemical and transportation equipment companies. In the ICT paradigm, the industries related with microelectronics, computers, telecommunications and information technologies, as well as, more recently, the Internet and also the new generation biotechnology, nanotechnologies and new materials. Each of these big techno-economic surges requires massive and adequate infrastructural investments. Some points should still be mentioned:

1) The increasing expansion of applications of the key factor, in the form of product and process innovations, is supported by new organisational forms and causes a general rise in potential productivity;
2) The emergence of new industrial branches emerges associated with a change in the relations between branches and the criteria of competitiveness;
3) The transition is accompanied by a wave of new investment opportunities and a deep reset of skills, not only of the workforce in general, but also of the management and technical staff;
4) The transition is accompanied by the transformation of institutions and social practices;
5) The paradigm shift can ultimately cause serious difficulties for countries that were at the forefront of the previous paradigm, when they are overridden by others in creating new products, industries, skills, etc. These are the periods in which the catching-up countries are more likely to try a leap in development (Perez, 1988).

In Perez' formulation, the institutional dimension has great importance. In her opinion, every economic boom is based "on a good match between a specific technological revolution and the forms of social and institutional management" (Perez, 1988, p. 86). This means that if a technological revolution is a necessary condition for the occurrence of a prolonged boom, it is not a sufficient condition, since it is necessary to get also a favourable institutional framework.

In the economics of innovation, a techno-economic paradigm shift implies thus the occurrence of a technological revolution, namely the emergence of "macro clusters" of radical innovations, based on new technological systems, and the existence of big institutional changes.

These considerations entail two implications: first, we need a theory of paradigm transitions, which in part has been built outside the field of economics of innovation by the community of system transitions, especially originated from economic sociology and science and technology studies (STS Studies). The second is that there is a need to pay more attention to what is going on in the technological domain specifically, where extraordinary advances have been taking place, some more typically based on scientific breakthroughs, other on progress in the fields of design, production engineering, monitoring and control, and systemation.

Two examples of renewable energies illustrate the two cases just mentioned. Wind power is in substance an update of the old motive source of mills and boats, having undergone an extraordinary technological renovation that comprises not only the wind turbines but also the research, measurement and monitoring schemes and devices of wind farms. Solar thermal energy had a similar path. However, the photovoltaic solar energy was based on huge scientific advances over more than a century, first applied in the field of space programs (Vallêra and Centeno Brito, 2006) and then translated to the current production of electricity.

Oddly, or maybe not really, the occurrence of these scientific and technological advances seem relatively neglected in the conventional milieus of the economics of innovation that continue to focus on the areas of ICT and biotechnology and virtually nothing to energy technologies. Nanotechnologies are a recent exception, with a rise of interest. Some authors admit that it can be the basis of a new technological revolution, taking the place ICT once occupied in the emergence and development of a new paradigm (Drechsler, 2010), but this is a minority view.

4. Freeman's view in 1992

More than two decades ago, Christopher Freeman wrote about the emergence of a new green techno-economic paradigm (TEP), concluding that: "It is therefore not soon to start thinking about and designing and building institutions and technologies which are likely to combine in a sixth (environmental) TEP" (Freeman, 1992:207). The starting point of his text is a retrospective appraisal of the impact of the 1972´s book *Limits to Growth*, by Denis Meadows, Donella Meadows and a MIT research team, which had a tremendous impact worldwide. Drawing on computational simulation models, the authors concluded that there were limits to the growth of production, consumption and population; and that the widespread adoption of the American growth style might lead to the general collapse of the whole system within just half a century. This collapse would be due to the depletion of key raw materials and the effect of an increase in pollution, both due to an industrial system highly intensive in energy and raw materials, albeit by then GHG emissions were still not considered.

In the debate which followed the publication of the MIT models of the 1970s on the limits to growth, two opposing parties were formed: the 'pessimists' (arguing for the 'zero growth') and the 'optimists' who included the SPRU and the author himself. The latter claimed that growth could and should continue into the 21st century – mostly because it would be ethically unacceptable and politically untenable to impose stagnation to the Third World countries - provided two conditions were met: the implementation of a set of institutional changes favouring a different world development path; and the reorientation of the R&D system with a shift in the rate and direction of technical change towards environmentally friendly objectives.

The updating of the MIT model, released in 1992, envisaged the possibility of growth. In twenty years, public and governments awareness on environmental problems had increased, and various initiatives had occurred, with a high point in the organisation of the Global Conference on the Environment in Rio, in 1992.

Yet, at the time he wrote, Freeman pointed out that the emphasis had been put on institutional change rather than technical change (Idem, p.191). Important progress had been achieved in reducing the energy intensity of final product in Europe and Japan, through an increase in the energy use efficiency and large-scale resort to recycling of raw materials, like aluminium. However, in his view, a much bigger effort was needed in the development of new technologies or the improvement of the existing ones[6]. The new ICT paradigm could provide a good starting point, for three main reasons:

1) ICT enabled a more effective monitoring and control of a wide range of industrial processes, favouring energy and materials saving; the management through electronic sensors and monitors of the energy used in buildings and homes; and the more efficient use of fuels in motor vehicles, aircraft, railways and ships.

2) ICT permitted a much more effective control of inventory and quality, therefore reducing defective or substandard products, which was associated with new management practices implemented in Japan, the United States and elsewhere.

3) ICT favoured the miniaturisation of technologies. Very Large Scale Integration in semiconductors technologies affected eventually all electronic devices, with a correlative saving of energy and materials. Miniaturisation, together with the increase of the processing speed, was indeed a key characteristic of the dominant technological trajectory in the computer industry.

Yet, the potential for development was enormous, as demonstrated by military applications and space exploration, but its fulfillment depended on political and societal choices not carried out yet. To begin with, these choices referred to the implementation of regulatory policies and a reorientation of R&D incentives led by environmental concerns. Second, they consisted of the adoption of new organisational forms resorting to (partially) working at home (the "electronic cottage"), alongside with a wider use of public transport, which also implied a change in political priorities. Freeman argued that these changes were mostly societal and political, and that the new technologies could only provide some support. He thought that in general terms the use of new forms of communication to reduce travel to work or business should be cherished, admitting however that the growing phenomenon of mass tourism came to contradict this hypothesis.

[6] He wrote: "Taking into account that since the Third World countries will almost inevitably increase their consumption of energy and materials as they industrialise and raise their living standards, the need for radical innovations in the energy industries and energy and materials-intensive activities is quite evident, as well as continuing incremental improvements". (Freeman, 1992, p.193).

The transformations foreseen as necessary entailed a vast array of implications. Among them one should stress the perception that a long-term policy was necessary; that a big stream of radical and incremental innovations had to take place “far beyond ICT” (Idem, p. 208) as well as radical price realignment “to reflect true long-term environmental costs and benefits” (Idem, p. 208). A long-term technology programme directed to the new paradigm, and involving innovators, potential users, universities and industry, should be launched, led by large and well-funded public labs working at an international scale; new technologies such as biotechnologies and nanotechnologies should be part of that multidisciplinary programme, in addition to ICT development. Freeman considered that a strong support from the world public opinion was necessary, with the commitment of entities like the United Nations and other international organisations and the involvement – as a key point - of countries of the so-called Third World.

5. State of art

More than two decades later, it is quite surprising to realize the actuality of the sharp vision of Freeman. That vision comprised the global dimension of the problems involved, the complexity of the solutions, the role of technological innovation in several domains (products, processes, technologies, organisational forms and the workings of firms and cities) and the role of policies, but also the need for changing lifestyles and public opinion, in both advanced and developing countries. To sum up, Freeman anticipated the transition to a new techno-economic paradigm, whose signs were already visible.

However, it is also surprising to notice the relative absence of this issue from the economics of innovation radar (or innovation studies) until very recently, that is, during two decades. Meanwhile, a new domain has emerged and organised over the last years on the subject of transition (or transitions) towards sustainability, with its research centres, graduate programmes, journals and conferences (see Markard, Raven and Truffer, 2012; Schot and Geels, 2007; Smith, Voß, and Grin, 2010). Eventually boosted by this new reality, which has strong links with innovation studies, reflection has been triggered within the innovation economics field.

In a book, which took stock and outlined the perspectives of the field (Fagerberg, Martin and Andresen, eds., 2013, *Innovation Studies – Evolution and Future Challenges*) two authors particularly addressed the environmental issue, assigning it great relevance. The first one is Carlota Perez (Perez, 2013), who included this issue as one of the four big questions of a future agenda for a paradigm shift with the correlate effects on the innovation conditions of the weakest and poorest[7]. Perez writes:

> "Both the planet and the economy need extensive 'green' innovation. The potential is there in technological terms. The ICT revolution can enable innovation across a wide range of sectors, from smart-grids to specialised materials, from redesigning products for durability and upgradeability to reducing the need for transport. But 'green' products and services are not capable of being immediately profitable, as many ICT products were at the beginning. The way to increase their economic viability is to induce a clear common direction. Convergence and networking can lead to synergies in suppliers and markets, increasing the profitability of the entire network. Markets alone cannot reach that outcome; an active government can" (Perez, 2013, p. 97).

Perez´s perspective is that of developing countries and her aim is the analysis of the ways they can thrive and innovate, meeting the new challenges. The pressure on natural resources, including energy, caused by the economic rising of a number of countries is among the big issues, addressed in the perspective of the constraints and eventual opportunities for those countries[8]. However, in my view, the text overlooks the magnitude of the global environmental problems, in spite of her call for launching a bridge towards the academic community organised around the study of transitions (Perez, 2013, p.103).

The second author electing sustainability as one of the main issues to be addressed is Luc Soete[9], when trying to answer the question whether innovation is always good. In his view, it is not. The first reason for this is that there is an excessive creative destruction, a "short-termism" of the creative destruction. In his own words, rather than creating value, innovation may be used to deliberately destroying it, through: "(…) a process of creative destruction in which innovation actually destroys the usage value of the existing stock of durable goods and as a result induces consumers to repeat their purchase" (Soete, 2013, p.136).

In line with Paul David - who questioned, in 2012, why not to consider excessive innovation as much a possibility as insufficient innovation and investment in R&D -, Soete analyses critically the post-war growth, in which "professional-use driven" innovation has continuously fed the creation of monopolistic profits through planned obsolescence and an unsustainable consumer

[7] The other three issues are: ICT, innovation, and market access by small firms in any country; flexible production and global networks; and natural resources.
[8] For instance, a drastic rise in the price of energy may lead to reducing the transportation of unprocessed materials favouring some kinds of local production in developing countries.
[9] The second issue are financial innovations – whose utility is not questioned - and their relationship with financial system failure. For Soete, the problem was a result of the system deregulation.

growth, what he calls "our ecologically unsustainable, innovation-led consumerism growth path" (Soete, 2013, p.136). His conclusion is that the environmental impact and ecological footprint of this model make it unsustainable in the developed world but also increasingly so in emerging countries, claiming for a shift in the process of research and innovation (Soete, 2013, p.138). The 'appropriate innovation' he defends should turn much more to the "bottom of the income pyramid"[10], giving as examples the fight against infectious diseases, water access and low price communications, etc.

This line of reasoning seems quite promising, firstly because it positions the direction and aims of innovation (innovate in what? at what pace? for what? for whom?) in the framework of a growth capitalist model which became incompatible with the basic equilibriums and conditions of the planet regeneration in a not so distant term.

The damages arising from the rapid pace and extension of creative destruction, particularly at social and ecological levels, are also referred to by Giovanni Dosi (Dosi, 2013, p.127) and Richard Nelson (Nelson, 2013, p. 190). The need for a transition towards a "green innovation" is defended by Ben Martin (Martin, 2013, p.173) and the need to take seriously into account global warming is stressed by Richard Nelson (Nelson, 2013, p.190). The action of the State is necessary to boost green technologies and renewable energies, according to Mariana Mazzucato (2013, pp.196, 197 and 199). Finally, "green growth and sustainable development" is one of the topics of the agenda for future research, summarised by Lundvall, where the launching of a large scale international project aiming to "clarify what the most important barriers to the development, application, use, and diffusion of renewable energy technologies are" is proposed (Lundvall, 2013, p.207).

Recent relevant texts offer comprehensive and systematic views on the way innovation can contribute the sustainability issue. This is the case of Perez (2013b; 2015), Laestadius (2015) and Mazzucato and Perez (2015), just to mention a few.

In a very recent paper, Perez argues that green growth will be favoured by the huge potential still unexploited of the information and communication technologies and will take place on the deployment stage of the present ICT techno-economic paradigm (Perez, 2015). She argues that innovative solutions will bring about sustainable growth and job creation, avoiding the pessimistic scenarios of de-growth and zero growth (Jackson, 2009). In the same vein, Mazzucato and Perez (2015) defend the idea of innovation as growth policy, to stress the centrality of innovation in the new era of growth.

[10] The author refers to Prahalad's book, "The Fortune at the Bottom of the Pyramid", 2005.

6. Final remarks

Although I substantially agree with the abovementioned authors, and endorse their views, I would suggest some aspects to be considered in a further more integrative approach of innovation and sustainability.

First, in order to address both environmental sustainability and the unemployment and rising inequality problems, a substantial shift in the direction of technological change should take place, towards a resource-saving trajectory, rather than a labour saving trajectory, which characterized all the economic history of advanced countries since the XX century (see Frey and Osborne, 2017). This topic is to be further developed.

Second, innovation has to be critically addressed, as Soete did (Soete, 2013), taking into account its two faces: economic prosperity and excessive creative destruction. The latter is purposefully implemented by business as a competitive weapon and as a means of creating new markets. Consumerism exerts a tremendous pressure on the resources of a finite planet, and is partly stirred by the shortened cycles of innovative products.

Third, the government action should rely on a vast array of policies to promote green growth: innovation policy, tax policy, regulation policies, redistributive policies, industrial policy, education policy.

Fourth, institutional innovation is of utmost importance, as Freeman stressed (1992), and at least as important as technological innovation to the transition to sustainable growth, both from the point of view of environment and social cohesion.

Fifth, theoretical tasks are to be conducted, namely the re-exam of the price system, the introduction of natural resources in economic calculus and the use of a stocks approach to complement the conventional flow approaches in economics.

References

Arthur, W.B. (1989), "Competing Technologies, Increasing Returns, and Lock-in by Historical Events", *The Economic Journal*, Vol. 99, No. 394, pp. 116-131.

Arthur, W.B. (1994), *Increasing Returns and Path Dependence in the Economy*, Ann Arbor, The University of Michigan Press.

Carlsson, B. and Stankiewicz, R. (1991), "On the nature, function and composition of technological systems", *Journal of Evolutionary Economics*, Vol. 1, No. 2, pp. 93-118.

David, P.A. (1985), "Clio and the Economics of Qwerty", *American Economic Review*, Vol. 75, No. 2, pp. 332-337.

David, P.A. (1994), "Why are Institutions the 'Carriers of History'?: Path Dependence and the Evolution of Conventions, Organizations and Institutions", *Structural Change and Economic Dynamics*, Vol. 5, No. 2, pp. 205-220.

Dosi, G. (2013), "Innovation, evolution, and economics: Where we are and where we should go", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 111-133.

Drechsler, W. (2010), "Nanotechnology, governance and public management: A techno-economic paradigms perspective", *NISPAcee Journal of Public Administration and Policy*, Vol. 3, No. 2, pp. 69-85.

EC (2006), *World Energy Outlook – 2050*, EWTO-H2, EUR 22038, Luxembourg, Office for Official Publications of the European Communities**.**

EC (2011), *Europe 2020 Flagship Initiative - A resource-efficient Europe*, *Communication from the Commission*, COM (2011) 21, Brussels.

Fagerberg, J., Laestadius, S., and Martin, B.R. (eds.), *The Triple Challenge for Europe – Economic Development, Climate Change and Governance*, Oxford, Oxford University Press.

Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.) (2013), *Innovation Studies – Evolution and Future Challenges*, Oxford, Oxford University Press.

Freeman, C. (1992), "A green techno-economic paradigm for the world economy", in Freeman, C., *The Economics of Hope – Essays on Technical Change, Economic Growth and the Environment*, London and New York, Pinter, pp. 190-211.

Frey, C.B. and Osborne, M.A. (2017), "The future of employment: How susceptible are jobs to computerization?", *Technological Forecasting & Social Change*, Vol. 114, pp. 254-280.

Geels, F.W. (2004), "From sectoral systems of innovation to systems", *Research Policy*, Vol. 33, Nos. 6-7, pp. 897-920.

Geels, F.W. (2010), "Ontologies, transitions (to sustainability), and the multi-level perspective", *Research Policy*, Vol. 39, No. 4, pp. 495-510.

Jackson, T. (2009), *Prosperity without Growth – Economics for a Finite Planet*, London, Earthscan.

Laestadius, S. (2015), "Transition Paths – Assessing Conditions and Alternatives", in J. Fagerberg, S. Laestadius and B.R. Martin (eds.), pp. 143-169.

Lundvall, B.A. (2013), "An agenda for future research", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 202-209.

Markard, J., Raven, R. and Truffer, B. (2012), "Sustainability transitions: An emerging field of research and its prospects", *Research Policy*, Vol. 41, No. 6, pp. 955-967.

Martin, B.R. (2013), "Innovation studies: An emerging agenda", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 168-186.

Mazzucato, M. (2013), "Smart and inclusive growth: Rethinking the State´s role and the risk-reward relationship", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 194-201.

Mazzucato, M. (2014), *The Entrepreneurial State – Debunking Public vs. Private Sector Myths*, revised edition, London, Anthem Press.

Mazzucato, M. and Perez, C. (2015), "Innovation as Growth Policy – The Challenge for Europe", in J. Fagerberg, S. Laestadius and B.R. Martin (eds.), pp. 229-264.

Meadows, D.H., Meadows, D.L., Randers, J. and Behrens III, W.W. (1972), *The Limits to Growth*, New York, Universe Books.

Mowery, D.C., Nelson, R.R. and Martin, B.R. (2010), "Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won´t work)", *Research Policy,* Vol. 39, No. 8, pp. 1011-1023.

Nelson, R.R. (2013), "Reflections on the study of innovation and on those who study it", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 187-193.

Perez, C. (1988), "New Technologies and Development", in Freeman, C. and Lundvall, B.A. (eds.) (1988), *Small Countries Facing the Technological Revolution*, London, Pinter, pp. 85-97.

Perez, C. (2010), "Technological revolutions and techno-economic paradigms", *Cambridge Journal of Economics*, Vol. 34, No. 1, pp. 185-202.

Perez, C. (2013), "Innovation systems and policy for development in a changing world", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 90-110.

Perez, C. (2013b), "Unleashing a golden age after the financial collapse: Drawing lessons from history", *Environmental Innovation and Societal Transitions*, Vol. 6, pp. 9-23.

Perez, C. (2015), "Capitalism, Technology and a Green Global Age: The Role of History in Helping to Shape the Future", *The Political Quarterly*, Vol. 86, S1, pp. 191-217.

Santos, F.D. (2012), *Alterações Globais – Os desafios e os riscos presentes e futuros*, Lisboa, Fundação Francisco Manuel dos Santos.

Schot, J. and Geels, F.W. (2007), "Niches in evolutionary theories of technical change – A critical survey of the literature", *Journal of Evolutionary Economics*, Vol. 17, No. 5, pp. 605-622.

Smith, A., Voß, J.P. and Grin, J. (2010), "Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges", *Research Policy*, Vol. 39, No. 4, pp. 435-448.

Söderholm, P., Hildingsson, R., Johansson, B., Khan, J. and Wilhelmsson, F. (2011), "Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050", *Futures*, Vol. 43, No.10, pp. 1105–1116.

Soete, L. (2013), "Is innovation always good?", in Fagerberg, J., Martin, B.R. and Andersen, E.S. (eds.), pp. 134-144.

Stern, N. (2009*), O Desafio Global – Como enfrentar as alterações climáticas criando uma nova era de progresso e prosperidade*, Lisboa, Esfera do Caos. (original edition: Stern, N., 2009, *A Blueprint for a Safer Planet - How to manage climate change and create a new era of progress and prosperity*)

Unruh, G.C. (2000), "Understanding carbon lock-in", *Energy Policy*, Vol. 28, No.12, pp. 817-830.

Unruh, G.C. (2002), "Escaping carbon lock-in", *Energy Policy*, Vol. 30, No. 4, pp. 317-325.

Vallêra, A. e Centeno Brito, M. (2006), "Meio século de história fotovoltaica", *Gazeta de Física*, Vol. 29, Nos. 1-2, pp. 10-15.

Van den Bergh, J. and Kemp, R. (2006), "Economics and transitions : Lessons from economic sub-disciplines", Working Paper Series, 2006-038, UNU-MERIT, Maastricht, 34 p.