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A New 'Cut' on Technological Innovation Aiming for Sustainability in a Globalized World

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A new ‘cut’ on technological innovation
aiming for sustainability in a globalized world

Adela Conchado[1], Pedro Linares[2]

Abstract: Innovation policy needs to respond to the complexity posed by sustainability goals and the globalization of innovation processes. Yet, current representations of technological innovation systems are not well suited to facilitate this view: they are built taking the diffusion of a technology as the main objective, rather than reflecting more broadly on its contributions to sustainability; and they have often focused on the interactions within a geography and not on interconnections among geographies. In this paper we propose a new ‘cut’ to technological innovation that puts the consideration of sustainability outcomes and international dynamics at its core: the Outcome-oriented Innovation Framework (OoIF). OoIF builds on key concepts from various strands of the innovation literature: innovation systems, innovation economics and sustainability transitions. We present the framework in detail, and provide a diagrammatic representation for it. We also reflect on its limitations, contributions and applications -particularly on how it allows to analyze the distribution of outcomes across differentiated activities and geographies.

Key words: technological innovation systems, innovation policy, sustainability, international dynamics, globalization

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1. Introduction

"Accelerating, encouraging and enabling innovation is critical for an effective, long-term *global response* to climate change and promoting economic growth and *sustainable development*" (United Nations, 2015a, emphasis added). This excerpt from the Paris Agreement in December 2015 condenses the expectations generated for innovation both as a needed response to sustainability challenges -in this case, climate change, as one of the most prominent nowadays- and as a potential source for prosperity. However, our understanding of how innovation policy could contribute to bringing these expectations to reality is still limited, particularly when reflecting on the intricacies involved in the highlighted terms: 'global response' and 'sustainable development'.

First, while innovation policies are often articulated at the national/regional/local level, they need to acknowledge the global dimension of some of the challenges they need to respond to -as the one posed by climate change-, and the global dimension of innovation processes -as knowledge networks, business activities, markets and institutional developments become increasingly globalized (Archibugi and Iammarino, 2002; Borrás et al., 2009). These globalization processes affect the extent to which countries/regions/localities are able to contribute to and benefit from innovation (Binz et al., 2017; Quitzow, 2015; Zheng and Kammen, 2014).

Second, having sustainability as the driving principle for development, urges us to take a critical view on innovation: we should not assume that innovation will bring about positive outcomes, but rather make an effort to assess its outcomes from an ample, long-term perspective coherent with sustainability: ample because it should go beyond economic benefits to incorporate the social and environmental; long-term because it has to recognize the long-lived effects of some technological impacts, and the cumulative and path-dependent nature of innovation - which means we need to care not only about observed outcomes now, but also about preserving the conditions and building the capabilities for future developments.

In this paper, we will further reflect on these two needs: the need to interpret innovation outcomes through the lens of sustainability (Section 2), and the need to consider explicitly the global dimension of innovation (Section 3), particularly in the context of clean energy technologies. We observe how our current representations of technological innovation systems are not well suited to consider these aspects: first, because they barely distinguish the outcomes of innovation but largely assume the diffusion of a technology as the goal to be pursued; second, because by focusing on dynamics within the boundaries of the system - typically defined by some geographical scope- they often disregard the dynamics among systems -and thus have paid limited attention to international dynamics.

In response to this gap, we propose a novel look at technological innovation that places the consideration of sustainability outcomes and international dynamics at its core: the Outcome-oriented Innovation Framework (OoIF). We will describe OoIF in detail (Section 4), reflect on its limitations, contributions and applications (Section 5), and summarize key insights of the paper as conclusions (Section 6)[3].

2. The need to interpret innovation outcomes through the lens of sustainability

2.1 What should technological innovation be for?

Although most studies on innovation do not tackle the question directly, there is usually an underlying assumption on them. Innovation studies have for some decades improved our understanding of the processes of technological change and policies to encourage it, often assuming positive outcomes of innovation for countries or regions pursuing it, linking it to long-run economic growth or socioeconomic progress – the '*innovation is good because it is good'* assumption. This was the case in both main strands of the literature, neoclassical and evolutionary, although with different underpinnings:

- The endogenous growth theory in the neoclassical view holds that investment in human capital, innovation and knowledge drive productivity gains that result in long-run economic growth (Aghion and Howitt, 1998; Romer, 1986).

- Evolutionary theory, and the literature on innovation systems built on its grounds, focused very much on the how and not so much on the why of innovation, often taking a Schumpeterian view on socioeconomic progress as a process of creative destruction

[3] Note that while this paper is eminently conceptual, in a complementary paper we have also explored the application of the framework to analyze the case of two renewable energy technologies -wind and solar PV- and discussed policy implications for energy innovation policy in the context of climate change negotiations (see Conchado and Linares, 2017).

(Fagerberg et al., 2010; Freeman, 1992; Freeman and Pérez, 1988; Nelson, 1990; Nelson and Winter, 1982; Schumpeter, 1942; Verspagen, 2001).

Now that we have reached a point in which we realize that our socioeconomic systems have become unsustainable in many ways (e.g. Rockström et al., 2009; Raworth, 2012), there is an increasing concern to make innovation work to enable more sustainable futures – the 'innovation is good only if *it is good*' assumption. In some way, there has been a shift in the underlying assumption about the contribution of innovation to prosperity: from emphasizing only the positive outcomes to emphasizing its double-edge potential to contribute to sustainability.

Thus, literature on innovation towards sustainability has exploded under various labels: sustainable technological change (Hekkert and Negro, 2009), sustainability-oriented innovation systems (Altenburg and Pegels, 2012) or, with a lot of traction lately, sustainability transitions (Markard et al., 2012; Smith et al., 2010). These studies normally emphasize the role of innovation to respond to environmental and social challenges– or to be more explicit, to transform our consumption-production models in sustainable ways (Weber and Rohracher, 2012).

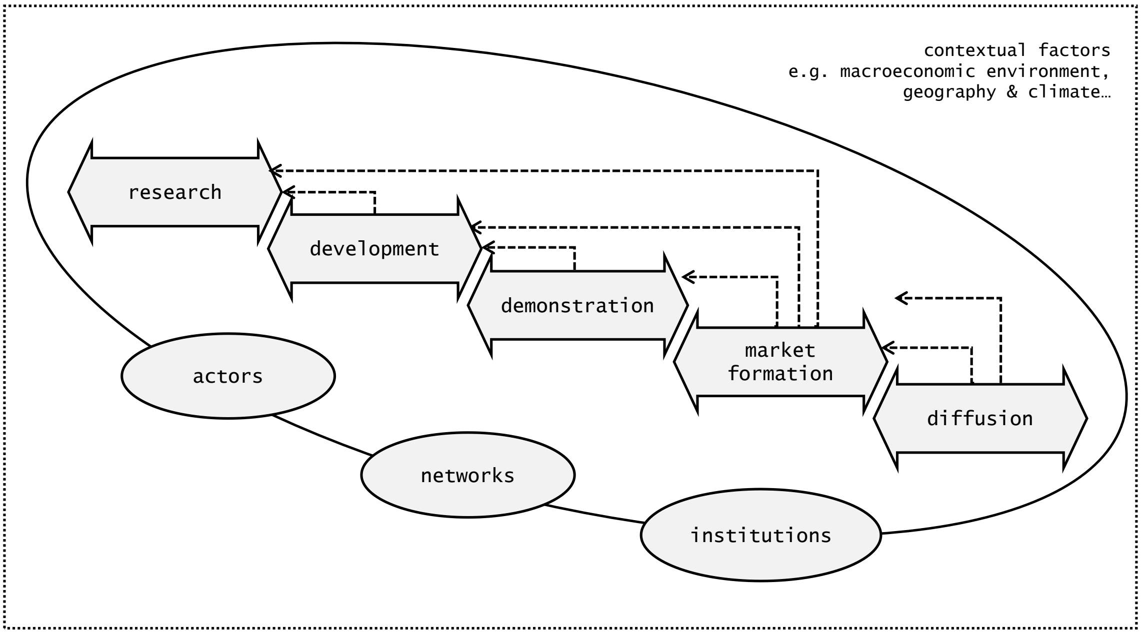
As we seem to converge towards sustainability as an adequate horizon to guide development –being the recent endorsement of the Sustainable Development Goals towards 2030 a remarkable sign of it (United Nations, 2015b)-, there is still the challenge of incorporating this view into innovation policy making and discourse. As expressed by (Weber and Rohracher, 2012): *"Current innovation policies nevertheless still put their main emphasis on economic growth and the ability of national economies or industrial sectors to generate innovations per se, but hardly deal with the challenges of more fundamental types of transformative change"*. It is therefore important to frame innovation policies in a way that is consistent with sustainability goals.

2.2 Our current understanding of technological innovation systems

The innovation systems literature has opened the 'black box' of innovation processes to study how innovation results from interactions among actors, networks and institutions (Edquist and Johnson, 1997; Lundvall, 2007). In the energy domain, the technological innovation system (TIS) approach has been widely used to study the development and diffusion of clean energy technologies.

The Energy Technology Innovation System (ETIS) constitutes a TIS-based approximation for a systemic interpretation of key variables and processes of technological innovation in the energy field (Gallagher et al., 2012; Grubler et al., 2012). ETIS is described as comprising "*all aspects of energy transformations (supply and demand); all stages of the technology development cycle (research, development, demonstration, market formation, diffusion); and all the major innovation processes, feedbacks, actors, institutions and networks"* (Gallagher et al., 2012). Figure 1 provides a representation of ETIS.

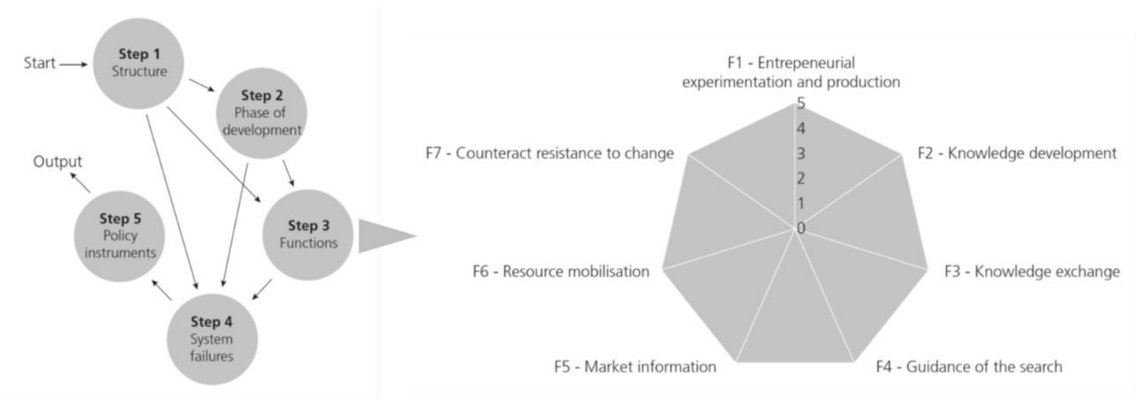
Figure 1: Energy technology innovation system



Source: Adaptated from (Gallagher et al., 2012)

Moreover, the functional approach to TIS (Bergek et al., 2008; Hekkert et al., 2007; Hekkert and Negro, 2009) provides an analytical framework to assess the functioning of the system and identify policy measures that respond to detected system failures. It relies on defining 'system functions' that are considered essential for the good functioning of the system, and identifying indicators (both quantitative and qualitative) for each of them. Figure 2 illustrates the policy analysis proposed by the functional approach to TIS (Hekkert et al., 2011).

Figure 2: Schematic of the policy analysis proposed by the functional approach to TIS



Source: (Hekkert et al., 2011)

The TIS approach has proven very useful to understand how a technology may reach wide diffusion. Indeed, it is frequently assumed that *"the primary goal of an innovation system is to contribute to the development and diffusion of innovation"* (Hekkert and Negro, 2009). However, we argue that policy-makers will seldom be interested in the diffusion of a technology per se, but by the contributions to welfare (in social, environmental and economic terms) it may have. We therefore suggest that innovation policy-making could benefit from an approach that facilitates the interpretation of innovation outcomes in a more coherent way.

2.3 Week/strong sustainability approaches to interpret innovation outcomes

Linking the discussion in 2.1 and 2.2, we suggest we should aim to interpret innovation outcomes through the lens of sustainability. Although there is no single interpretation of what constitutes 'sustainability', and a careful consideration of the concept is beyond the purpose of this paper, it is worth mentioning that while some interpretations focus on the idea of generating value (weak sustainability approaches), others focus on establishing limits (strong sustainability approaches). We argue that both approaches are useful and indeed complementary (Romero and Linares, 2013), not less so when thinking about how technological innovation can contribute to sustainability.

The outcomes associated to innovation activities can be interpreted as variations in capitals (human, social, environmental and economic capital) –following a common approximation from the weak sustainability approach (Neumayer, 2003)-, whereas setting the direction of innovation may benefit from establishing clear thresholds (e.g. limiting emissions to keep CO_2 concentration below certain limits) –which resonates with the strong sustainability approach. Even when distributional considerations are not sufficiently incorporated in either the weak or the strong sustainability approaches, the pursuit of equity should constitute a fundamental concern for sustainability (Pearce, 1988).

Technological innovation activities can contribute to increase or maintain capitals in various ways: producing new knowledge increases human capital (K_h), manufacturing and commercializing new technologies increase economic capital (K_e), adopting green technologies can reduce the impact on natural capital (K_n), and encouraging interaction or developing institutions to foster innovation may well increase social capital (K_s). The weak sustainability approach thus can provide a useful basis to interpret the outcomes of the innovation process as variations in capitals. From a strong sustainability approach, we need to keep our systems beyond critical levels, and thus technological innovation should work towards that. Although the idea has mostly been developed for ecological limits, we could also think of social or economic limits. Establishing thresholds can work as clear objectives to mark the direction for our socio-technical systems[4].

3. The need to incorporate explicitly the global dimension of innovation

3.1 The increasing relevance of international innovation dynamics

Literature on the geography of innovation has emphasized the importance of location and proximity for innovative activity (Feldman and Kogler, 2010), as co-location favors knowledge spillovers among proximate actors, and the 'stickiness' of capabilities and the tacit component of knowledge means it cannot easily be transferred to other settings. However, while innovation dynamics at the local level remain important, the globalization

[4] Note that while this conceptualization of the contribution of innovation to sustainability may sound quite theoretical, it has a rather direct application in policy making. On the one hand, raising capitals may translate into easily recognizable policy goals, such as fostering economic activity through manufacturing or service provision (K_e), reducing emissions through the installation of renewable technologies (K_n), or generating capabilities to invent or produce new technologies thanks to research and development activities (K_h). On the other hand, setting clear sustainability goals is also a common practice, being the SDGs and the agreements to reduce emissions achieved in COP21 the most notorious examples nowadays.

The increase of social capital is less easily recognizable as a clear policy goal, but the quality and inclusiveness of institutions is indeed acknowledged as a fundamental condition for the prosperity of nations (Acemoglu and Robinson, 2012), and reforming them to incorporate the views of "*impoverished, marginalized, and unborn populations*" as critical for enabling sustainable development (Anadon et al., 2016). Indeed, increasing the inclusiveness of institutions (Ks) may precisely hold the clue to progress in the equity dimension of sustainability.

of trade, production and knowledge networks involve a reconfiguration of innovation dynamics at a global scale (Crevoisier and Jeannerat, 2009; Henderson et al., 2002; Lorentzen, 2008; Narula and Dunning, 2000). For instance, greater international job mobility, global access to information, offshoring of R&D activities, multilateral research cooperation, or international training are all contributing to a greater internationalization of knowledge flows.

This reconfiguration of innovation dynamics is having profound implications for the development and models of industrial catching-up. According to (Binz and Anadon, 2016), technological upgrading in some industries in latecomer countries such as China is happening not only through their integration in global value chains, or through diversification to sectors related to their pre-existing capabilities, but by mobilizing resources from the 'global technological innovation system'. While conventional mechanisms for technology transfer and the building of absorptive capacity used to be at the center of discussion for bringing technological innovation to developing countries, a broader conception of the globalization of innovation invites us to rethink traditional North-South approaches (Brewer, 2008) and to consider a wider variety of potential international linkages (Ernst, 2002).

3.2 The challenge for innovation policy-making in a globalized context

The globalization of innovation processes poses fundamental questions to innovation policy-making. On the one hand, there is a growing concern that governmental efforts to support innovation could *"vanish into global-related processes"* (Borrás et al., 2009), and the perception of *"a higher risk of 'winners and losers'"* (Archibugi and Iammarino, 1999). On the other hand, globalization can also mean greater opportunities for innovation, both due to the enlargement of markets and to the expanding potential for ideas as more people engage in innovation processes (Tabarrok, 2011). In this respect, international collaboration and policy coordination for innovation in energy technologies could be a promising avenue (Gallagher et al., 2006; Grau et al., 2012; Lema and Lema, 2012; Lester and Hart, 2011).

In view of the globalization of innovation dynamics and the potential of international linkages, policy-makers need to interpret how the innovation processes in their countries/regions relate to those in other countries/regions, both to improve their understanding of how the outcomes of innovation could get distributed and to pursue strategies that encourage positive cross-national relationships.

Indeed, from the perspective of a country/region, it is no longer enough to frame policies as if the benefits of innovation processes could be kept inside its borders. As expressed by Quitzow (2013), *"competitive success depends not only on applying an appropriate governance framework at home (…), it is equally important to understand and respond to the dynamics of international competition and technological change"*. Or in the words of Mazzucato (2015): *"we'll continue to spend our time imagining success until we recognize that innovation unfolds as part of a global process"*.

Moreover, from a global perspective, understanding innovation in renewable technologies as a cross-national process is particularly relevant in a time when we are trying to advance collective agreements to reduce emissions that include efforts to propel innovation in clean technologies on a global scale. Already in 2002, Sagar and Holdren (2002) stated that "*much more systematic effort is warranted to assess, and fill, the gaps in understanding of the global energy innovation system – only then we will able to develop appropriate policies to guide this system to enable it to meet future challenges*".

In the innovation systems literature, TIS approaches have typically made little emphasis on cross-national relationships, with most studies focusing on country-level analyses (e.g. Jacobsson and Bergek, 2004; Negro et al., 2008; Reichardt et al., 2016). However, recent studies have highlighted the importance of transnational dynamics to understand the evolution of some technologies and the innovation benefits countries are able to capture, particularly in the field of renewable technologies (Binz et al., 2014; Coenen et al., 2012; Gosens and Lu, 2013; Quitzow, 2015; Vasseur et al., 2013; Wieczorek et al., 2015).

Therefore, in our attempts to interpret innovation outcomes, we should aim to incorporate explicitly international dynamics, so as to grasping how globalization processes affect the realization of outcomes across different geographies.

4. OoIF as a framework to interpret sustainability outcomes of technological innovation in a globalized context

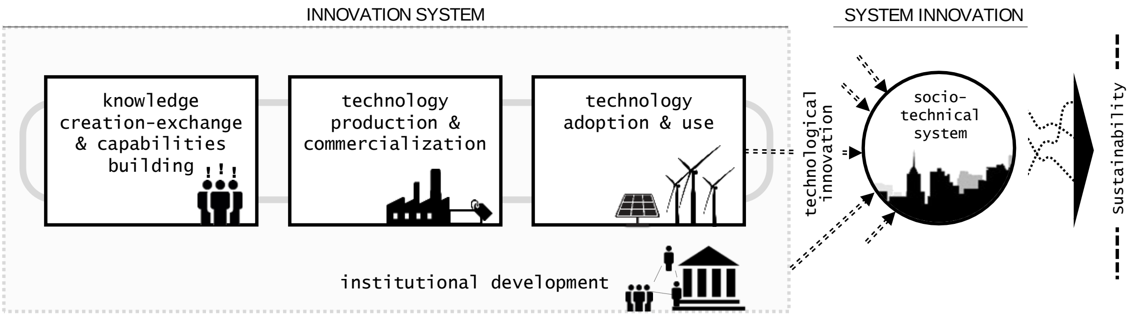
We have just discussed how a view on innovation systems that puts considerations of sustainability outcomes and international relationships could be useful for innovation policy-making. Responding to this need, we propose the Outcome-oriented Innovation Framework (OoIF).

In building this framework, we rely on previous literature on innovation systems (IS), innovation economics and sustainability transitions to borrow and integrate in a novel way some of the concepts they have developed. To describe it, we will use diagrams as a visual synthesis of the conceptualization of innovation systems we suggest, and also in an attempt to provide a useful tool for innovation policy analysis[5].

4.1 System definition and building blocks

Following the discussion in Section 2, we propose that the purpose of technological innovation should be interpreted through the lenses of sustainability, realizing that the implications of technological innovation on sustainable development arise both from the innovation process itself –with different types of innovation activities leading to differentiated but interrelated types of outcomes- and from the integration of technology into a certain socio-technical system that can evolve through different pathways –with some pathways being more conducive to sustainability than others. Building on this understanding, we turn now to propose the basic structure and building blocks for OoIF, as represented in Figure 3 (OoIF-bb).

Figure 3: OoIF-bb - Schematic of building blocks in the Outcome-oriented Innovation Framework



Crucial to OoIF is the consideration that the *innovation system* can feed *system innovation* (which brings together these two strands of the literature often presented separately)[6]. The

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[5] Although trying to capture highly complex innovation processes into a diagram bears the risk of oversimplification, it also provides an opportunity to present ideas in a way that can be more easily understood and made operational. In the literature we can find interesting examples like the chain-linked model (Kline and Rosenberg, 1986), or the representation of the multi-level perspective (Geels, 2002), both offering powerful diagrammatic representations of complex concepts and dynamics.

[6] An important appreciation is that both 'innovation system' and 'socio-technical system' are constructs that allow us to dissect the overall reality to study certain aspects of it. As such, their boundaries may be blurred and fluid (e.g. some actors may be involved in both, changes in the institutional set-up of the innovation system

innovation system can be interpreted as interconnected innovation activities (represented as boxes), which can be clustered by the type of capital they contribute to generate or preserve. As a result of these innovation activities, new technologies or improvements in existing technologies get introduced into a *socio-technical system* (represented as a circle) that works towards the fulfilment of a certain societal need. The socio-technical system receives other sources for change, like shifts in social norms, organizational structures, business models or policy frameworks (represented as arrows directed towards the circle). Technological innovation together with these other forms of innovation result in the socio-technical system constantly evolving. The evolution of the overall system is path-dependent (represented as three alternative paths), and can be guided by visions and long-term objectives that set the direction (e.g. emission cuts; represented as a triangle). Indeed, direction becomes a critical consideration in the context of sustainability: it is no longer only about accelerating innovation processes, but about reflecting where those innovation processes take us and aiming to favor sustainability-oriented trajectories (Stirling, 2009).

Within the innovation system, we cluster innovation processes into four innovation-related activities: (1) *knowledge creation-exchange and capabilities building*; (2) *technology production and commercialization*; (3) *technology adoption and use*; and (4) *institutional development.* For brevity, we will later refer to these activities as Knowledge-Production-Adoption-Institutions, respectively, or their initials: K-P-A-I.

Activities K-P-A are chosen to be aligned with easily identifiable outcomes (which can be linked to increasing capitals): respectively, increase knowledge and capabilities (Kh), foster economic activity (Ke), improve service or performance -in the case of renewable technologies, improve environmental performance (Kn)[7]. They are also easily related to

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may be having a direct effect in the socio-technical system, etc.). We still find the distinction useful for analytical purposes, as it allows to focus the analysis of innovation processes around a specific technological domain, while keeping in mind its integration into the wider socio-technical system where many other aspects beyond the studied domain of technological innovation become relevant. Although the scope of the innovation system could be defined by a combination of technological/sectoral and geographical/institutional boundaries, we will use OoIF assuming the innovation system corresponds to that of a given technology in a given country. Note that if we broaden the scope of the innovation system enough to include all innovation-related activities (all technologies and sectors) in the country, the innovation system would then correspond to the overall knowledge-production-consumption-institutions system of the country.

[7] This does not mean that variations in capitals are only affected by these activities, or that each activity will only be linked to a single type of capital -it just intends to highlight the capital that is most critically involved in each activity. Furthermore, it is important to notice how capitals are mutually interdependent: e.g. human capital is arguably fundamentally depending upon social capital (Lundvall et al., 2002).

common policy fields: respectively, RD&D/education – industrial policy/entrepreneurship – sectoral policy (energy). Note also that activities P and A belong to the production-consumption system that is called for sustainable transformation.

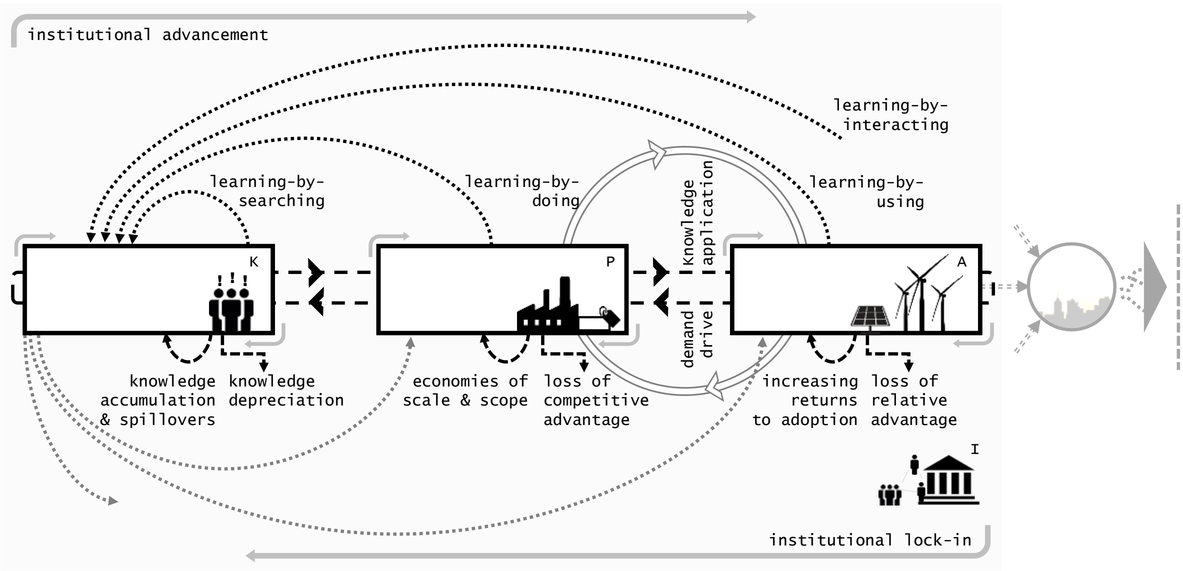
Activity I is a critical component of the innovation system. It represents the institutional setting, composed both from codified rules or regulations and uncodified values and interactions, in which all other innovation activities are embedded, co-evolving with it. Here we find the interactions, organizational cultures, consumer values, policies or power struggles that play a crucial role in shaping the innovation process.

The activities chosen are all indispensable for technological innovation to happen, as successful new technologies need to be invented, produced and adopted, and this will always happen in a given institutional set-up. Note however that these activities are not presented as stages in a process, as these activities can happen simultaneously and interconnectedly. Note also that these activities do not aim to represent clusters of actors in any way, as each activity will typically involve more than one actor (e.g. knowledge generated at research centers, industries, consumer experience…), and often actors will be involved in more than one activity (e.g. businesses can be engaged not only in technology production and commercialization, but also in knowledge creation and exchange, and in the adoption of new technologies).

4.2 Dynamics within the innovation system

We will explore now in more detail the left hand-side of Figure 3 to identify dynamics within the innovation system, as represented in Figure 4 (OoIF-dw). Even if dynamics internal to the system are not the focus of the framework, they are essential to grasp the systemic functioning of innovation.

Figure 4: OoIF-dw - Schematic of dynamics within the innovation system



A quick overview of Figure 4 can reveal various types of dynamics. Activities K-P-A are interlinked through a recursive process working in two directions simultaneously and interrelatedly (represented as a closed loop or carousel): new knowledge is constantly being applied to develop new or improve existing products or services that try to find its way into the market -knowledge application- while demand is constantly signaling or opening up opportunities for technological improvements to be realized -demand drive. All activities K-P-A-I require some preexisting knowledge and capabilities to be developed (wide semicircular loops pointing out from K), and involve some learning that feeds back to K (wide semicircular loops pointing towards K). Activities K-P-A may also be affected by self-reinforcing dynamics (small feedback loop in each activity), and weakening dynamics due to competing alternatives (leakages). Note that we have used dotted arrows to represent all these dynamics, trying to imply that they are not, by any means, linear or certain. Activity I is responsible for institutional dynamics that could work in favor or against innovation, in what we have called institutional advancement or lock-in respectively (long arrows working in opposite directions). Besides influencing the overall system, these institutional dynamics may affect activities K-P-A in particular ways (small arrows around each activity). We have also included a circular flow connecting P and A to represent the potential to recuperate technologies, components or materials and reincorporate them to productive processes (in line with *circular economy* approaches).

Overall, these dynamics represent an entangled mixture of knowledge-related, market-driven and institutional forces, which we will further describe next. Even when we will organize the discussion that follows by breaking it under the headings *knowledge dynamics, market dynamics* and *institutional dynamics,* note this categorization is not unambiguous, since the entangled nature of the dynamics makes it difficult to provide a clear-cut categorization.

a. Knowledge dynamics

Knowledge plays a pivotal role in our framework. We deal with it at a rather macro level, and not at the level of interactions between agents, networks and institutions (as it is normally the case in IS studies). However, by defining activity K as 'knowledge creation-*exchange* and *capabilities* building' we would like to acknowledge implicitly two key insights from the IS literature: 1. that new knowledge is often generated through interactions -e*xchange*- (Malerba, 2002), and 2. that innovation requires more than pure knowledge, it requires the competencies and skills -*capabilities*- to transform it into new technological applications (Bell, 2009; Dosi et al., 2008; Morrison et al., 2008).

It may also be worth noticing that by knowledge we are not only referring to scientific knowledge or other 'technical' forms of knowledge, but also to knowledge related to developing innovative business models (Boons et al., 2013) or creating adequate institutional and policy frameworks (Mytelka and Smith, 2002), to the locally embedded forms of knowledge that feed grassroots innovation (Seyfang and Smith, 2007), and to knowledge generated among communities of users leading to user-centered innovation (Hippel, 2005). Thus, actors involved in activity K may include researchers, users, policy-makers, managers, analysts, activists, technicians, entrepreneurs, etc.

Knowledge and capabilities are needed to develop all innovation-related activities (K-P-A-I), and all activities in turn tend to involve some learning that increases knowledge and capabilities[8]. Depending on where the knowledge/capabilities are created, we can distinguish different types of learning dynamics that feed back to K: *learning-by-searching, learning-by-doing, learning-by-using* and *learning-by-interacting* (Lundvall and Johnson, 1994).

The feedback for *knowledge accumulation and spillovers* suggests the cumulative and combinatorial nature of knowledge generation (Strambach and Klement, 2012) -i.e. new

[8] Some studies suggest that learning effects may not always be positive -see e.g. (Grubler, 2010) on the case of nuclear scale-up in France.

knowledge builds upon preexisting knowledge (Scotchmer, 1991; West and Iansiti, 2003) and often from readapting it across disciplines, technologies, sectors, organizations or regions (Audertsch and Feldman, 2004; Nemet, 2012). Knowledge may also be lost or become obsolete, in what could be termed *knowledge depreciation* (Grubler and Nemet, 2014).

b. Market dynamics[9]

Central to our model is the bidirectional connection between knowledge generation and markets: new products or services reaching the market will often be the result of the iterative combination of new knowledge being transformed into industrial or commercial applications -*knowledge application*- and reacting to identified or created market needs -*demand drive*[10].

Weakening dynamics may appear in the domain of each activity, often due to the development of outperforming competing alternatives that disrupt the value of the ongoing activity. Beyond *knowledge depreciation*, already described, we could have *loss of competitive advantage* in P (Porter, 1998), or *loss of relative advantage* of the technology in A (Holak and Lehmann, 1990), both in terms of cost/price and performance. We could also find self-reinforcing dynamics: *economies of scale and scope* for P[11] (Grubler, 2012), and *increasing returns to adoption* for A -which may be caused by network externalities, fad or herding effects, technology lock-in, etc. (Jaffe et al., 2003)[12].

c. Institutional dynamics

The institutional context largely affects technological innovation processes. For instance, interactions among actors allow knowledge to diffuse and be created in K, the entrepreneurial

[9] We include under this somehow loose heading effects emerging from the interaction with competing alternatives, from some economic forces affecting the activities, and from the interplay of knowledge creation with adoption markets.

[10] These processes can be linked to the technology push and demand pull perspectives in innovation studies (Di Stefano et al., 2012) and their application to innovation policy-making (Peters et al., 2012). However, OoIF invites to see these processes in relationship with other innovation-related dynamics and enables to think of policy options beyond the technology-push/demand-pull framing.

[11] Diseconomies of scale are also possible (Isoard and Soria, 2001).

[12] Note again that these dynamics are not purely economic (and indeed we could argue that the causes behind increasing returns to adoption are mostly institutional). Relatedly, we could notice how other dynamics have relevant economic implications: e.g. learning processes drive down production and installation costs -learning curves and learning rates, despite their limitations, are often used to describe this process (Jamasb and Köhler, 2007; Söderholm and Sundqvist, 2007).

environment and attitudes affect the probability of new business endeavors in P, and shared expectations among investors or favorable consumer preferences may create the conditions for new markets to emerge in A. Indeed we can consider institutions as the ‘substrate’ in which all innovation activities and dynamics take place, co-evolving with them (Nelson, 1994). In fact, it is not only about institutions affecting technological change, but also the other way around: institutions evolve affected by technological developments and other sources of change.

Public policy, as a particular form of institution, may play a crucial role in supporting innovation in various ways: by eliminating market barriers, by creating systemic conditions for it, or by actively spurring it (Geels et al., 2015; Mazzucato and Semieniuk, 2017). This may be particularly true in the case of clean energy technologies to be able to overcome carbon lock-in (Unruh, 2000). Indeed, demand in the case of renewable technologies may be largely attributable to governmental actions (Nemet, 2009), to the extent that we could even talk of a “policy-driven market”[13] (Quitzow, 2015). The role of regulation in the energy context is also critical, as it can potentially enable or stifle innovation (Kiesling, 2010; Lo Schiavo et al., 2013).

Overall, in OoIF we consider two simplified dynamics working in opposite directions as an overall result of all the institutional activity: *institutional advancement* working in favor of the innovation process (e.g. simplified procedures for installation), and *institutional lock-in* hindering the innovation process by reinforcing established development pathways, particularly when the new technology challenges incumbent interests (e.g. electricity market not well adapted to introduce intermittent generation). We may also consider how these dynamics may affect activities K-P-A in particular ways.

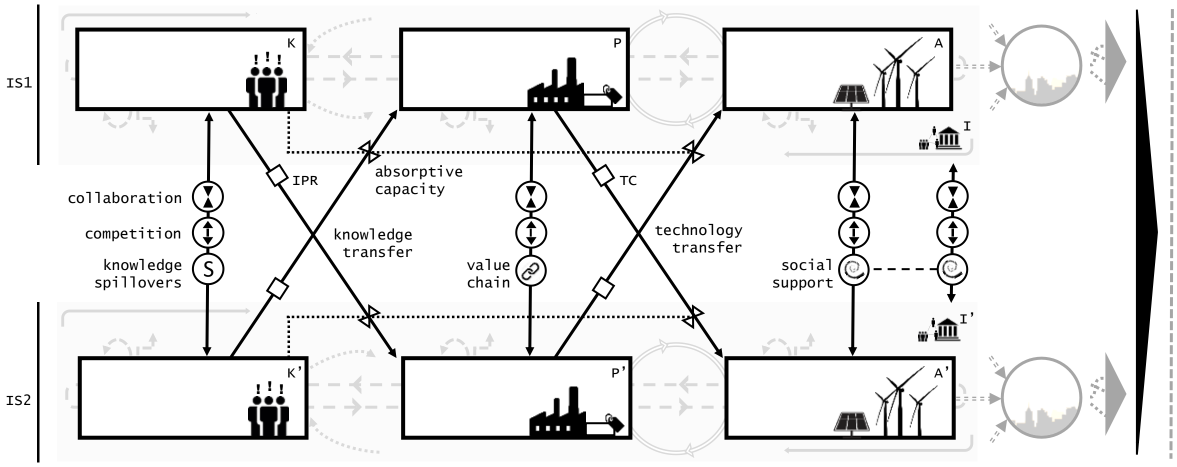
4.3 Dynamics across innovation systems

If we consider the boundaries of the innovation system in OoIF correspond to those of a country, by studying the relationship across innovation systems we will be studying cross-

[13] This is another good example of how knowledge, market and institutional relationships are intertwined: in this case, we could say institutions are, to a large extent, creating the market through deployment policies, and also guiding knowledge creation through research, development and demonstration (RD&D) policies.

national dynamics. In Figure 5 (OoIF-dx) we explore these relationships connecting two innovation systems: IS1 and IS2.

Figure 5: OoIF-dx - Schematic of dynamics across innovation systems



We need to recognize that the broadening of innovation networks at the international level is the result of complex webs of cross-national relationships happening among multiple actors (people, businesses, governments and other organizations), at various scales (local, regional, national, transnational), and through many possible channels (commercial, relational, etc.). It is therefore difficult once more to provide a clear-cut categorization. In any case, we specify in our framework some types of cross-national dynamics that, based on evidence from the literature, can be considered relevant for innovation processes.

In particular, we consider technology transfer across countries, highlighting the role of absorptive capacity enabling or hindering them, and acknowledge the role of Intellectual Property Rights (IPR) mechanisms to prevent knowledge generated in one system to be applied for commercial purposes in other system. Certain technological characteristics (TC), such as modularity and shippability, will also affect the extent to which technologies can be exported. We identify coexisting forces of competition-collaboration happening between same-type activities, and also some particular relationships for each type of activity: knowledge spillovers, value chain, and trends in social support.

Before further describing these dynamics, note that we have included an additional triangle at the right-hand side of Figure 5 to represent global direction. The agreements resulting from climate conferences (COPs) or the 2030 Agenda for Sustainable Development are probably the most prevalent manifestations of the attempts to achieve a global vision that could signal the direction for technological innovation (and of development in general).

a. Competition-collaboration

Competition and *collaboration* relationships, often of an entangled nature, are possible for each type of activity. Examples of collaboration may include research partnerships, joint ventures, collective purchase or global governance efforts, respectively for K-P-A-I. Examples of competition may include competition for talent, competition in manufacturing cost, competition for physical and financial resources, or confrontational trade policy, respectively for K-P-A-I. Note that competition-collaboration relationships, broadly speaking, may occur both at the firm and the governmental levels, affected by both market and policy dynamics.

The effect of business competition on innovation is not clear, with some studies suggesting a U-shaped relationship: certain degree of competition may spur innovation as companies attempt to gain competitive advantage, while too much competition may stifle innovation as companies focus on short-term cost efficiency (Aghion and Griffith, 2005; Aghion et al., 2005).

Collaboration is increasingly being recognized as an important potential source of innovation (Katz and Martin, 1997; Malerba, 2007; Metcalfe and Coombs, 2000; WEF, 2015), also specifically in the context of renewable technologies (IEA, 2010; Philibert, 2004). The open innovation approach (Chesbrough, 2003), that has spread notoriously not only among businesses but even influencing the European Union’s vision on science and innovation (EC, 2016), may be considered in some way a collaborative approach to innovation. As examples of R&D and technological collaboration increase, governance rules emerge to handle collective invention (Foray and Steinmueller, 2003).

b. Technology transfer

Technology transfer (TT) dynamics play a key role in enabling knowledge or technology to move between innovation systems (Popp, 2010) -but of course not indiscriminately. *Absorptive capacity* appears as a key enabler of TT (Cohen and Levinthal, 1990): existing knowledge and capabilities determine how much knowledge or technologies can be incorporated from outside the system (Escribano et al., 2009; Kneller, 2003). *Intellectual Property Rights* (IPR) also play a relevant role in modulating technology transfer for commercial applications across countries, although there is no consensus on to what extent they work as barriers or incentives for innovation (Abdel-Latif, 2015; Cimoli et al., 2014).

Technological characteristics (TC) may also critically affect the ways and extent in which TT can be realized (Huenteler et al., 2016).

OoIF allows to distinguish forms of TT by which knowledge 'travels' to be applied in the productive sector -e.g. through patent licensing, consulting or franchising; what we could perhaps more appropriately be called *knowledge transfer*-, from TT by which the final product or service reaches new markets -e.g. through international trade or leasing agreements; what we have called *technology transfer*. To be considered TT, we could argue that these processes should involve in any case some learning in the recipient country (Pueyo et al., 2011) -which, following OoIF, would feedback to K and increase the absorptive capacity of the country to further enable TT.

c. Knowledge spillovers

For activity K, *knowledge spillovers* can represent a key cross-national relationship (Bosetti et al., 2008). Even when they are closely related to the TT processes just described, by knowledge spillovers we refer to the unintentional, often disembodied 'travelling' of knowledge. Although not all knowledge or capabilities can be transferred easily, and arguably knowledge spillovers happen primarily intranationally (Branstetter, 2001), other forms of proximity -such as cognitive, organizational, social or institutional (Boschma, 2005)- may diminish the relevance of geographic proximity and allow knowledge to move between countries. Sources of knowledge spillovers across countries may be reverse engineering, knowledge diffusion through publications or media, labor mobility, or imitation of successful implementation models.

d. Value chain

For activity P, related to manufacturing and commercialization, *value chain relationships* may be worth considering (Morrison et al., 2008; Pietrobelli and Rabellotti, 2010). While we represent *technology production and commercialization* as a single activity, we need to recognize that in reality it is composed by a great range of activities: product design, manufacturing of components, integration of parts, software development, project development, project execution, operations and maintenance… In the highly globalized world we live today, these activities may well be distributed across different countries (Zhang and Gallagher, 2016). Given that the value generated by each of these activities will be different, understanding value chain relationships across countries can be crucial to understand the innovation benefits they are able to capture.

e. Social acceptance/support

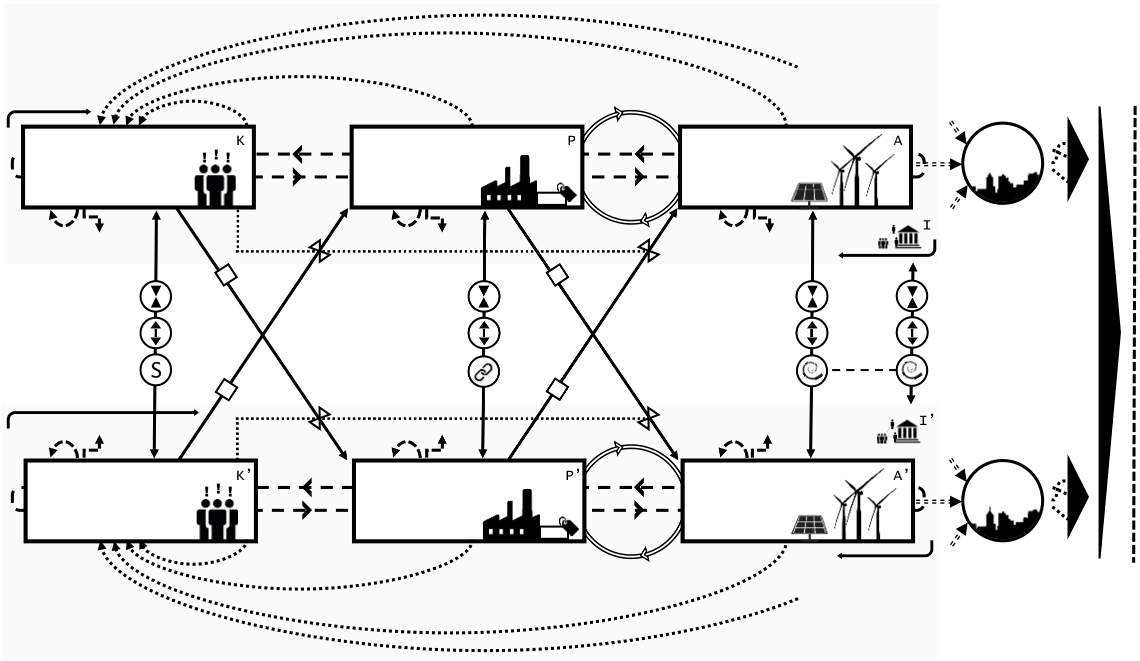
For activities A and I, we suggest that trends in *social acceptance* -perhaps better framed as *social support* (Batel et al., 2013)- may be a relevant interaction across countries. Social acceptance can be defined in various dimensions, namely socio-political, community and market acceptance (Wüstenhagen et al., 2007). Public perceptions on the technology (West et al., 2010) and how narratives influence them (Stirling, 2014) may be crucial in determining its overall social acceptance. We also need to be aware of how the type of technology and project design affects social acceptance processes –e.g. social acceptance dynamics for domestic micro-generation installations can be expected to be very different to those of large scale power plants (Sauter and Watson, 2007).

The growth in adoption of a technology may create trends affecting users, investors or policy-makers in ways that favor wider diffusion of the technology, also across borders (Busch and Jörgens, 2005). We locate this relationship as operating between A and I because it is mainly through the transformation of institutions -e.g. shared user preferences, decision-maker attitudes or investor expectations- that trends get generated. Indeed, we could say that the adoption of a technology and the development of institutions are entangled in a process of co-evolution (Nelson, 1994).

4.4 Full representation of OoIF

Overall, the framework we have just proposed, OoIF, builds on concepts that have been widely acknowledged and developed in the literature but offers a novel look at them, integrating them into a visual framework specifically conceived to reflect on the distribution of innovation sustainability outcomes across activities and countries. It presents technological innovation as a systemic process that is both cumulative and exposed to leakages or disruption through intertwined knowledge, market and institutional dynamics that go beyond national boundaries. It also acknowledges how technological innovation gets introduced into a certain socio-technical system in which together with other factors for change can generate systemic transformation towards sustainability. Figure 6 provides the schematic diagram of the overall framework.

Figure 6: OoIF – Schematic diagram of the overall framework



5. Discussion on the limitations, contributions and applications of OoIF

5.1 Limitations

It goes without saying that OoIF does not aim to capture the full complexity of innovation processes. Some of its main shortcomings include its limited ability to represent the underlying structure of the system and the interactions among actors, networks and institutions (as innovation systems frameworks do), to consider agency and power (beyond the very limited representation of institutional activities we provide), to reflect technological detail or technology lifecycle considerations (beyond acknowledging the role of certain technological characteristics in determining exportability), or to contemplate financial and material resource flows.

OoIF also presents limitations in the way it frames the connection between innovation and sustainability. The aspects of sustainability that are better incorporated are the preservation or generation of value (as variations in capitals) and the importance of the direction of innovation as it transforms socio-technical systems (guided by the respect to limits), while consideration of distributional aspects within systems is very limited (beyond acknowledging the role that institutions may play in promoting equity). Further consideration on the connection of innovation processes to societal needs and values, legitimacy and accountability (Ely et al., 2014), and to diversity, inclusivity and adaptation to local contexts

(Leach et al., 2012; STEPS Centre, 2010), would also be important when trying to guide innovation towards sustainability.

An important, related consideration is that OoIF in principle does not distinguish between public and private efforts and outcomes, but assumes both are intertwined within the system, in a similar vein as how the innovation systems literature considers innovative results as "a combination of private and public goods" (Lundvall et al., 2002). However, it may be relevant to clarify the distinction when assessing innovation efforts and innovation outcomes. Regarding efforts, we need to remain aware of the distinctive and complementary roles that both businesses and government can have to promote innovation. Thus, for instance, some forms of technology transfer such as joint ventures or licensing will depend fundamentally on businesses, while governments may propel international cooperative efforts in basic RD&D or trade agreements. Regarding outcomes, we assume that innovation activities may lead to positive variations in capitals that would in turn allow for increased wellbeing, but do not explore the intricacies of how innovation outcomes get distributed among governments, companies and people, or particular subgroups of them, which would nevertheless be important to understand to what extent and for whom innovation activities translate (or not) into improvements in wellbeing[14].

In any case, the diagrammatic representation of the framework attempts to be some sort of 'prototype' of the proposed conceptualization, open for discussion and reconfiguration. We remain very aware that diagrams are always a simplified interpretation of reality, but we also appreciate how they provide a 'tangible' basis to discuss ideas. Are the building blocks we have chosen the most adequate? Are we missing relationships? Are we misinterpreting the role of certain dynamics? We believe diagrammatic representations may facilitate the discussion and further refinement of ideas.

5.2 Contribution

If we think of innovation processes as a sphere full of complexity inside, we can interpret different strands in the innovation systems literature as providing different 'cuts' to the

[14] This would require a very careful analysis, as it may be affected by numerous factors, such as tax systems, policy instruments, public budget structure, international trade regulations, or corporate social responsibility practices.

innovation reality, ready to reveal certain aspects of it. In this paper we propose OoIF as a new 'cut' of innovation processes, one that is more ready to reveal the distribution of innovation outcomes across differentiated activities and geographies. In doing so, we largely drift away from the IS tradition, as we lose the focus on interactions to put it on welfare-generating activities.

We could summarize the conceptual contributions and relative strengths of OoIF in the following points:

- Built specifically to interpret the outcomes of technological innovation through the lens of sustainability, particularly as resulting from innovation processes (contribution to welfare as variations in capitals), but also in terms of direction (awareness of socio-technical pathways).

- Integrates consideration of dynamics from different strands of innovation studies: economic and market dynamics (neoclassical economics), knowledge and institutional dynamics (innovation systems), and transformational dynamics (sustainability transitions).

- Incorporates the consideration of international dynamics affecting the innovation system and provides some structure to interpret cross-country relationships -largely missing in current frameworks.

- Provides a diagrammatic representation that may facilitate the reconfiguration of the framework itself and its application for innovation policy-making.

5.3 Applications

In a working paper complementary to this one (Conchado and Linares, 2017), we offer a practical application of OoIF. We used OoIF to analyze the developments in wind and solar PV technologies across countries in the period 2000-2013. We identified indicators for OoIF's activities -patent counts, exports, installed capacity, etc.- and represented their evolution in the most relevant countries for these technologies. We also collected evidence in the literature to appreciate the importance of international dynamics in these processes. This allowed us to analyze how global innovation processes have unfolded across countries, and reflect on policy implications in the context of climate change negotiations. We found the perspective offered by OoIF was useful to provide a novel look at the evidence[15].

Beyond this application of OoIF as the basis to analyzing global developments in certain technologies, we believe OoIF could be useful to support diagrammatic reasoning for innovation policy making. In our view, OoIF could provide some basis to:

- Clarify goals of innovation policy in terms of type of expected outcomes (increase in different types of capital linked to innovation activities) and consideration of directionality (oriented to meet sustainability goals and guided by the respect to limits). Also, complementarily, evaluate results of innovation policy from an ample, long-term perspective –that goes beyond 'industrial success' of a given technology as the virtually single criteria for evaluation.

- Identify specific innovation-related activities or dynamics that need to be tackled, particularly those related to cross-national interactions. Also, potentially, offer some structure to analyze the integration of multiple policy levers into policy mixes.

- Consider innovation strategies for countries that are outcome-oriented and aware of their relationships in the global innovation landscape.

- Reflect on the distribution of efforts and results across countries for multilateral initiatives, and propose ways to improve the functioning of the global innovation system in response to global challenges such as climate change, taking advantage of innovative forms of cross-national relationships.

Finally, even when OoIF has been conceived with the case of energy technologies in mind (particularly renewable energy generation technologies), in building it we have attempted to capture some fundamental innovation dynamics acknowledged in the literature not necessarily restricted to the energy sector. Anyhow, further analysis would be needed to test the usefulness of the framework in other technological domains.

[15] At least in two ways: first, by showing the importance of differentiating innovation outcomes and appreciating their distribution globally -as we saw how the type and share of outcomes countries have realized from innovation in both solar PV and wind technologies varies greatly across them and in time; second, by showing how international dynamics have become crucial to understand the outcomes countries are able to realize.

6. Conclusions

In this paper we have suggested that innovation policy could benefit from a representation of technological innovation that puts the consideration of sustainability outcomes and international dynamics at its core -offering a complementary perspective to current technological innovation system approaches. We have proposed and described in detail the Outcome-oriented Innovation Framework (OoIF) in response to this gap in the literature.

OoIF presents technological innovation as a systemic process that is both cumulative and exposed to leakages or disruption through intertwined knowledge, market and institutional dynamics that go beyond national boundaries. It also acknowledges how technological innovation gets introduced into a certain socio-technical system in which together with other factors for change can generate systemic transformation towards sustainability. Overall, it integrates in a novel way key concepts from the literature on innovation systems, innovation economics and sustainability transitions.

The proposed framework is represented in a highly visual way to enable diagrammatic reasoning, both from the perspective of a country interacting with other countries for innovation policy-making, and from a global perspective for the search of collective solutions to a shared challenge as the one posed by climate change. While acknowledging the limitations of the framework (indeed, we insisted in presenting OoIF as an additional 'cut' to innovation complexity complementary to other 'cuts' in the literature), we suggested OoIF can provide some useful basis for framing innovation policy aiming for sustainability in a globalized context.

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