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ENERGY INNOVATION POLICY
in response to global challenges and the quest for sustainable prosperity

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"The real voyage of discovery consists not in seeking new landscapes,

but in having new eyes"

Marcel Proust

Agradecimientos

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Summary

This thesis synthesizes my journey in trying to understand how energy innovation policy could contribute to alleviating global sustainability challenges while generating welfare for countries. It has been a fascinating journey touching on many disciplines and fields of research (energy economics, innovation systems, sustainability transitions, development, globalization, strategic management…). In the process, I have come up with a framework that helps to understand how the innovation outcomes a country is able to realize depend not only on how well it is able to build its innovation system (where the focus has mostly been recently), but also on international dynamics, as knowledge, production, markets and institutional developments become increasingly globalized. We show how this has been the case for both solar PV and wind technologies, and we derive policy implications for both countries and international climate change negotiations.

Resumen

Esta tesis recoge la síntesis de mi viaje tratando de entender cómo las políticas de innovación en energía podrían contribuir a la vez a resolver los grandes retos globales y a generar bienestar para los países. Ha sido un recorrido fascinante a través de múltiples disciplinas y campos de estudio (economía energética, sistemas de innovación, transiciones a la sostenibilidad, desarrollo, globalización, gestión estratégica…). En el proceso he desarrollado un marco conceptual que permite entender cómo los beneficios de la innovación que un país es capaz de materializar dependen no sólo de lo bien construido que esté su sistema de innovación (donde se ha venido poniendo el foco últimamente), sino también de las dinámicas internacionales, a medida que el conocimiento, la producción, los mercados y los desarrollos institucionales se globalizan. Mostramos como esto ha sido así en los casos de las tecnologías solar fotovoltaica y eólica, y extraemos implicaciones para el diseño de políticas, tanto desde el punto de vista de las políticas nacionales de innovación como del de las negociaciones internacionales de cambio climático.

How to read this thesis

If you are interested in the **conceptual discussion** of the perspectives currently influencing our approaches to innovation policy and how this thesis adds to them by offering a **novel framework**, you can find this in **Chapter 3** and **Chapter 4**.

If your focus is on the **empirical analysis** of the cases of wind and solar PV, and the discussion of **policy implications** from the observed international innovation dynamics, you can find them in **Chapter 5** and **Chapter 6**.

In case you are interested in a diagnosis of the **state of energy innovation in Spain** (as in 2013), you could read **Chapter 2** in isolation of the rest.

For an **overview of contributions** of the thesis, go to **Chapter 7**.

If you want to get a flavor of the thesis without going into the academic writing, look for the **boxes with the silhouette of a ship**. In these boxes you will find some key **insights of the thesis illustrated through a metaphor:** *innovation as a sailing journey*.

Finally, if you are curious about **interdisciplinarity**, you are invited to read **Annex A**. Here I have allowed myself to express how this thesis has challenged my initial assumptions on what a thesis should be. I thought sharing this might be useful for some others struggling in the muddy, yet -I believe- rewarding journey of interdisciplinarity.

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Chapter 1_

Introduction.

A thesis on strategic energy innovation policy -through the lens of sustainability

Introduction. A thesis on strategic energy innovation policy -through the lens of sustainability

In this first Chapter, we would like to introduce how the topic of this thesis is relevant and how we are going to develop it in this document. We will begin by reflecting on the context and motivation for the thesis, introducing the crucial role of energy innovation to respond to sustainability challenges and its potential as a source of welfare (Section 1). We will then review some fundamental concepts on which the thesis is grounded, namely what energy innovation is and why energy innovation policy is needed (Section 2). We will close the chapter by describing the purpose, scope and contents of this document (Section 3). Along the chapter, we will also introduce a metaphor for innovation -*innovation as a sailing journey*- that can help us understand some of the involved complexities and later, in future chapters, illustrate the insights and propositions developed in this thesis.

1. Context and motivation for the thesis

Energy remains essential for a country's economic development and social wellbeing. In order to reach development levels similar to those of the more developed countries, many developing countries will need to increase their energy consumption, and many will definitely seek to do so in the coming years. Moreover, a large share of the world's population still lacks access to advanced forms of energy (according to IEA's estimates, more than 1,400 million people lack access to electricity and 2,700 million still cook with traditional biomass). If access to modern forms of energy increases, global energy consumption will be significantly affected.

Thus, we can expect more resources will be needed to meet this growing demand for energy services, a demand that will clash with the finite nature of fossil fuels and other natural resources needed for producing, transporting and consuming energy. This scarcity has already led to significant increases in the prices of some resources and to the higher volatility of those prices, with the consequent negative effects on the economy, both global and of individual countries.

Moreover, fossil energy resources are also contributing to the creation of large-scale environmental problems. Both global warming, induced by increased concentrations of greenhouse gases in the atmosphere, and air pollution, caused by other regional or local pollutants, with their associated damage to health and ecosystems, are due largely to the production and consumption of energy. Indeed, the threat of global warming above tolerable levels is leading many countries, including notably those in the European Union, to consider large-scale decarbonization of energy systems.

This challenge can only be tackled by combining an effort to moderate energy consumption and an effort to supply the remaining consumption with low-carbon technologies. There is no doubt that energy savings and energy efficiency will have to play a remarkable role. However, the potential of savings and efficiency, despite being large, is limited. For Spain, for instance, we could consider feasible (technically and economically) savings of 40% by 2030 (Economics for Energy, 2011), in line with the estimates of similar studies for other countries. Could we increase those savings further? And how are we going to supply the remaining demand? Here is where innovation becomes essential: we need new technologies, or significant improvements to existing ones, that could allow us to cover our global energy needs in sustainable ways.

Fortunately, energy innovation is regarded not only as a need, but also as an opportunity. The development of new energy technologies can become a source of socioeconomic value, by creating business opportunities, generating employment, or increasing knowledge and capabilities. Indeed, there is the expectation that technological lead and/or market lead (Beise and Rennings, 2005) in energy technologies can bring about significant socioeconomic benefits (Sagar and van der Zwaan, 2006). Broader discourses around ‘green growth’ (Pérez, 2016) also emphasize the idea that new forms of producing and consuming energy could result in the next development leap.

Unfortunately, innovation processes face many obstacles, related to market failures and institutional and systemic barriers, which make innovation productivity insufficient. In the case of the energy sector, liberalization processes may well have contributed to this situation, as environmental and social considerations become typically less relevant in the decision-making of private companies than in the decision-making of public companies. Ultimately, the existing failures and barriers to the innovation process (further developed in Section 2.2) mean that markets alone cannot produce the innovation that society needs, and public policy becomes essential.

Thus, although the governments of many countries have worked for decades to enhance domestic innovation with different degrees of consistency and success, their role seems to be increasingly necessary to achieve the required transformation in the energy sector, given the challenges it faces, and the more knowledge we have about the importance of having an aligned, consistent, and efficient innovation system.

However, from the perspective of policy makers in a country or region, and given that resources are scarce, it is not about supporting any energy innovation, but the energy innovation that most enhances welfare in the country. This requires them to define an energy innovation strategy well suited for their country or region, particularly given the need to prioritize the use of limited public resources, and the increasing difficulty in achieving and maintaining competitive positions in the global economy.

With this PhD thesis we aim to contribute to improving our understanding of how we could strategically approach energy innovation policy, so it can respond to global sustainability challenges while contributing to improving welfare in countries.

Box 1: Introducing the 'innovation as a sailing journey' metaphor that will be used to illustrate various arguments and propositions along the thesis

Innovation as a sailing journey...

Why do people/ businesses/ countries embark on innovation? In my view, the answer may have much in common with the reasons that once led people/ businesses/ countries to embark on large ships in the search of new lands: a combination of need and opportunity, the willingness to take risks on the expectations of achieving a better life.

As in the search for new lands, the search for new technologies is full of uncertainty. The sailors departing in those large ships could not be sure where the chosen route would take them, or even if the unfolding events would allow them to explore the chosen route at all or instead would take them through some alternative routes they could not anticipate.

Those stories of discovery ended with some ships reaching new lands, some ships coming back home with empty hands, and some ships sinking into the sea... How could those sailors increase their opportunities to succeed in finding new lands?

And how could we, nowadays, increase our opportunities to succeed in producing innovation that contributes to improving our lives in sustainable ways? This question is what took me on the journey of this PhD thesis… Now, the ship sets sail!

2. Fundamentals

We will review now what energy innovation is and why energy innovation policy is needed. Note that this overview aims to represent just a starting point to develop the thesis, and indeed in the coming chapters we will extend and even challenge in some ways the often-held assumptions reflected in this section.

2.1. What is energy innovation?

Innovation can be defined very broadly as the introduction of new things, ideas or ways of doing something[1]. However, if we attempt to be more specific, we could argue that 'innovation' involves the *application* of ideas with some degree of *novelty* which result in some *improvement*. We have highlighted application, novelty, and improvement as the three key aspects that the term 'innovation' often implies.

This broad definition means innovation could be anything from the development and diffusion of new or improved technologies (*technological innovation*), the realization of new business models or novel strategies (*business innovation*), advances in the way we acquire knowledge and skills (*educational innovation*), changes in the way we handle processes and relationships within organizations (*organizational innovation*), or improvements in our rules and patterns for interaction (*institutional innovation*).

Although large transformations as the one required for energy systems to get sustainable will tend to require the combination of all forms of innovation, we will focus in this PhD thesis on technological innovation, while acknowledging the relevance that other forms of innovation (such as new business models or institutional developments) play in allowing the diffusion of technological innovation. Indeed it is important to realize that technological innovation cannot be really isolated from other forms of innovation, as technologies operate in what could be described as 'socio-technical systems' (Geels, 2004).

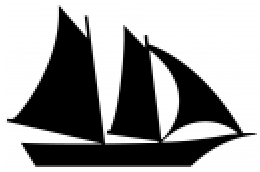
It is important to distinguish innovation (a process) from invention (an event) -invention may be considered an antecedent to innovation, and innovation as an antecedent to technological change (Ruttan, 1959). It is also important to note the difference between incremental and radical innovation, or between sustaining and disruptive innovation (Christensen and Overdorf, 2000). Whereas incremental innovation offers relative improvements within existing markets or socio-technical structures, radical innovations create new markets or challenge existing socio-technical structures, and can potentially transform them in fundamental ways.

[1] Oxford Advanced Learner's Dictionary: oald8.oxfordlearnersdictionaries.com/dictionary/innovation

Box 2: Innovation as a continuous process

We never step on dry land, we are always sailing

There is something that makes current innovation efforts very different to those former journeys in the search of new lands, though. The outcomes of innovation are much more difficult to grasp than the outcomes of those discovery trips, as they are much less tangible and much more dynamic. Unlike those journeys, innovation efforts have no clear beginning and no clear end: we constantly build on previous developments, even if we don't realize, and those coming after us will build on our developments too. Indeed, innovation is a continuous process. *We never step on dry land, we are always sailing*.



By 'energy innovation' we are referring to innovation affecting in some way how we produce and/or consume energy. Since energy is rather ubiquitous, this definition may include novel applications in a broad range of activities linked to energy extraction, conversion, distribution or consumption, and in activities needed for those such us equipment supply, engineering or managerial activities (Anadon et al., 2011). However, the applications in the thesis will mostly refer to technological innovation in energy generation, and in particular to innovation in renewable electricity technologies.

2.2. Why is energy innovation policy needed?

Policy intervention to support innovation in energy technologies is often considered essential to overcome market barriers associated to knowledge and environmental externalities (Jaffe et al., 2005), to create systemic conditions that favor interactions and learning (Chaminade and Edquist, 2010), and to channel development towards sustainable trajectories (Geels and Schot, 2007).

Regarding market barriers, there are some barriers that are common to innovation in any sector. Perhaps the most notorious is that related to the public good nature of knowledge. Knowledge is non-excludable (or not perfectly excludable), as it is transferred relatively easy: we observe how ideas cross borders even when intellectual property rights are in place. Besides, knowledge is non-rivalrous, meaning that the use of knowledge by some people does not limit the ability of other people to use it. Indeed, it is sometimes quite the contrary: the more people use knowledge, the more they can benefit from it. These public good characteristics of knowledge imply that generating knowledge provides benefits for society as a whole, but those generating knowledge may not be able to capture the benefits sufficiently to compensate for their efforts. As a consequence of these 'knowledge spillovers', we tend to generate less knowledge than what would be socially optimal.

The market barrier just described (knowledge spillovers) and other barriers that can be associated with energy innovation (environmental externalities, information asymmetry and incompleteness of financial markets) are summarized in Table 1.

Table 1: Market barriers for innovation

Market barrier	Explanation
Knowledge spillovers	Knowledge is non-excludable (or not perfectly excludable) and non-rivalrous -> benefits difficult to be captured by the private sector -> less investment in knowledge than socially optimal
Environmental externalities	Markets do not currently incorporate most environmental costs -> lower share of cleaner technologies than socially optimal
Lack of information or information asymmetry	Insufficient or asymmetrical information limits the adoption of cost-effective solutions by the consumers, particularly those related to energy efficiency[2]. In some cases, this is further exacerbated by the "principal-agent problem"[3].
Incompleteness of financial markets	Lack of investment for high technology risk profiles > realization of the "valley of death" –stage in which funds that are needed to take innovation to the next level cannot be found (Weyant, 2011)

Moreover, as we have come to understand how innovation processes result from complex interactions among actors, networks and institutions, we have also become aware how there may exist some gaps or limitations in the functioning of the innovation system. These may include institutional problems (e.g. mismatches between basic and applied research, limited technology transfer, or poor educational systems), interaction problems (e.g. poor networks among actors and institutions, or too closed networks), lack of capabilities (e.g. lack of funds, lack of knowledge, learning difficulties) or lack of infrastructure (e.g. insufficient or poor-performing research centers) (Negro et al., 2012).

[2] Bounded rationality is an additional barrier (although not strictly a market barrier). Bounded rationality recognizes that even if consumers knew the most cost-effective solution, they would sometimes not choose it (for instance, when they prioritize low upfront cost over long-term savings).

[3] The principal-agent problem refers to those cases in which the party that makes the decision and the party that bears the consequences are not the same, and their interests are not aligned. The most common example is landlord-tenant case: an energy efficiency investment may be cost-effective for the tenant (who pays the energy bills), but not for the landlord (who would incur in the investment but would not realize the savings in the energy bills).

On top of the market and institutional barriers already mentioned, which are common for innovation of every kind, we may consider some barriers that are more specific to the energy sector. The characteristics of the energy sector that may hinder innovation include:

- technological lock-in –present in many sectors- is exacerbated in the energy sector by the large and long-life investments required (Unruh, 2000).
- investments to develop energy technologies are often too large and too risky for the private sector.
- there are powerful incumbents in the energy sector that lobby to maintain status quo.
- there are many actors and institutions involved, which complicates the coordination of efforts, particularly when there is not a clear energy strategy that serves as a guide.
- the sector is dominated by large publicly traded companies that tend to prioritize short-term results over the long-term ones that innovation could bring.
- there are high levels of uncertainty, both related to technological development and to regulatory conditions.
- electricity and fuels are commodities, which hinders differentiation as a strategy to deliver competitive advantage.

The existence of all these barriers associated to energy innovation means that market alone is not able to deliver innovation in the scale and direction needed to achieve sustainable energy systems. Public policy to support contributing-to-sustainability energy innovation thus becomes essential.

3. Purpose, scope and contents of the thesis

"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). This excerpt from the Paris Agreement in December 2015 condenses the expectations generated for innovation both as a needed response to climate change and as a potential source for prosperity. As we have just discussed, energy innovation policy will need to play a remarkable role to make this happen. In this PhD thesis, we would like to contribute to advancing our understanding of how we could improve energy innovation policy to indeed make it happen.

The background analysis provided in **Chapter 2** provides a detailed assessment of the current situation of energy innovation in Spain (based on indicators) and an estimation of potential benefits (based on model simulations). This analysis will allow us to verify that there is much room for improvement in energy innovation policy, and that the rewards for that improvement could be significant. We also provide some general policy recommendations that emerge from the analysis, among which we identify one as particularly interesting to be explored: the need for strategic approaches for energy innovation policy-making that allow countries to place their innovation efforts in an effective way -one that allows them to advance towards more sustainable energy systems while realizing welfare-improving benefits. How could countries undertake energy innovation policy more strategically?

With that research question in mind, we address the literature review in **Chapter 3**, where we explore the meaning of strategy in the context of energy innovation policy and the implications of globalization, review the different perspectives that shape our understanding of innovation processes and innovation policy-making, and assess to what extent existing frameworks could enable strategic thinking. We detect a lack of frameworks enabling the consideration of differentiated outcomes and of international dynamics -which, as we found out in the process of exploration, are becoming increasingly relevant to understand the outcomes a country can realize.

Indeed, while policies are often articulated at the national (or perhaps regional or local) level, the globalization of knowledge networks, business activities, markets and institutional developments is affecting the extent to which countries are able to contribute to innovation processes and benefit from them (Binz et al., 2017; Quitzow, 2015a; Zheng and Kammen, 2014). The implications of these globalization processes are substantial both from the perspective of a country and from a global perspective.

From the perspective of a country, it is no longer enough to frame policies as if the benefits of innovation processes could be kept inside national 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"*.

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 (COPs) 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*".

Yet, we lack a framework that helps us understand how innovation activities and their associated outcomes are distributed across countries, and -complementary- how the global innovation process comes together through the aggregation of developments across countries. We will argue that our current forms of conceptualizing innovation systems (IS), which highlight interactions within national/ regional/ sectoral/ technological boundaries (NIS, RIS, SIS and TIS frameworks), are not well suited to facilitate this view. First, because they barely distinguish the outcomes of innovation but largely assume positive socioeconomic benefits. Second, because by focusing on dynamics within the boundaries of the system they often disregard the dynamics among systems.

Thus, in **Chapter 4**, we will propose a framework specifically conceived to understand the distribution of innovation activities and their associated outcomes across countries: the Outcome-oriented Innovation Framework (OoIF). 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. The exploration of the dynamics that affect and link these activities takes us to integrate concepts not only from the IS literature, but also from innovation economics and sustainability transitions. Thus, OoIF assumes the innovation system can feed system innovation towards sustainability, and incorporates the consideration of knowledge, market, and institutional dynamics.

OoIF is built around four innovation-related activities with differentiated outcomes – namely, knowledge creation-exchange and capabilities building; technology production and commercialization; technology adoption and use; and institutional development-, which are linked through dynamics both within the system and across systems. This is all represented in a highly visual way to enable diagrammatic reasoning, both from the perspective of a country interacting with other countries for strategic 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.

In **Chapter 5**, we will use OoIF to analyze the developments in wind and solar PV technologies across countries in the period 2000-2013. We identify indicators for OoIF's activities -patent counts, exports, installed capacity, etc.- and represent their evolution in the most relevant countries for these technologies. This allows us to present in a highly visual way how global innovation processes have unfolded across countries. We then use evidence from previous studies to appreciate the importance of international dynamics in these processes.

We see how innovation activities within countries' borders seem to be decoupled in various cases -e.g. a country excelling in generating patents may be taking a modest role in technology production or adoption, or a country investing heavily in the installation of a technology may be doing so without bringing about new knowledge developments or production capabilities. However, when broadening the view to appreciate global interactions, it becomes apparent how activities do feed each other across borders -e.g. industrial production in some countries increases to feed growing installation in foreign markets. Indeed, some changes in the evolution of innovation activities can only be explained by cross-national interactions -e.g. patent licensing across countries leads to the development of a successful industry in the receiving country. In short, the case of wind and solar PV in recent years illustrates how innovation in renewable technologies is happening at a global scale, how different countries are contributing to it in different ways and in turn being able to capture different outcomes, and how global dynamics may be very relevant.

In **Chapter 6**, we will discuss the policy implications of these observations, both from a national and a global perspective. First, from the perspective of a country, national innovation policies targeting renewable technologies should carefully consider the position of the country in the global innovation landscape, both to define policy expectations in terms of outcomes (e.g. jobs, exports, etc.) and to incorporate initiatives to better take advantage of transnational dynamics. Second, from a global perspective, if the collective goal is to accelerate the transition towards cleaner energy systems, we need to make the global innovation system work as effectively as possible while ensuring viable paths for countries.

In this regard, there seems to be great potential in cross-national collaboration, for which we need to find ways to share risks and benefits of pushing innovation forward. Although this is yet an underexplored path (as most innovation efforts so far have been framed nationally or regionally), current efforts such as the Mission Innovation initiative following COP21, or the Technology Facilitation Mechanism announced to support the implementation of the Sustainable Development Goals (SDGs), are already advancing in this direction. OoIF can be used to facilitate the analysis of the distribution of innovation activities (and the investments and benefits associated to them) across countries, in order to find better ways to collectively pursue innovation towards global sustainability.

In **Chapter 7** we offer some conclusions for this PhD thesis, including research contributions, policy implications and applications, and future lines of research.

Chapter 2_

Background

Understanding the relevance of energy innovation policy through the case of Spain

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The content of this chapter is based on the policy brief that summarized the 2012 *Economics for Energy* annual report "Energy innovation in Spain: Analysis and recommendations", written in collaboration with the Belfer Center at Harvard University. The full report can be found (in Spanish) in the website of *Economics for Energy:* http://eforenergy.org/actividades/Presentacion-de-Informe-Anual-de-Economics-for-Energy-sobre-la-innovacion-en-energia-en-Espana-.php

Background: Understanding the relevance of energy innovation policy through the case of Spain

In Chapter 1 we have suggested how energy innovation is crucial to advance towards more sustainable energy systems and how it can provide opportunities for socioeconomic progress, and also how energy innovation policy is needed to trigger the realization of these benefits. In this chapter we would like to explore more deeply these ideas by analyzing the case of a particular country: Spain.

The need to transform the energy system in sustainable ways is definitely applicable to the Spanish situation. Spain is a country heavily dependent on foreign energy (in 2011, the energy trade balance contributed 88% to the deficit of the Spanish trade balance[4]), with the consequent risks in the supply price and impact on the competitiveness of the Spanish economy. Regarding environmental impacts, there has been a negative trend for greenhouse gas emissions in Spain since the early nineties, and there is a raising concern about local pollution problems.

Realizing opportunities to generate socioeconomic value and employment would also be critical for Spain, particularly after some years of severe economic crisis in the country. Spain has a relatively developed industrial infrastructure in certain areas of the energy sector and may be well positioned to realize these opportunities. However, capturing those possible future benefits would require an adequate design of innovation policies.

This Chapter will revolve around three key questions. First, *are we putting adequate efforts on energy innovation?* Based on the analysis of indicators, we provide a diagnosis of the current state of energy innovation in Spain and the barriers it faces (Section 1). Second, *what benefits can we expect from energy innovation?* Here we present a partial evaluation of the potential benefits of energy innovation, focusing on the savings that could be realized in the energy system if we increased our investment in energy R&D (Section 2). Third, *how could we improve energy innovation in Spain?* Based on the previous analysis we provide a set of recommendations for the Spanish government to stimulate energy innovation (Section 3). Finally, all these analysis and recommendations will serve as the basis to better define the research question that will guide this PhD thesis (Section 4).

[4] Data from the Spanish Ministry of Economy and Competitiveness

1. Are we putting adequate efforts on energy innovation?

In this section we synthesize our analysis of the current situation of energy innovation in Spain (the full analysis can be found on the 2012 Economics for Energy annual report "Energy innovation in Spain: Analysis and recommendations"). Even if this analysis is based on the evaluation of multiple indicators (as illustrated in the figures and tables included in the report), we focus here on summarizing the key insights that emerge from the analysis.

1.1. Investment in energy R&D

First, the Spanish expenditure (both public and private) in energy R&D is low compared to other sectors. Part of the explanation for this lies in the liberalization of the energy sector that took place since the late eighties. Indeed, the expenditure in energy R&D was greatly reduced at that time and has remained at very low levels since then. However, not everything can be blamed on liberalization: the expenditure in energy R&D in Spain is also very low when compared to that in neighboring countries (including those in which the energy sector has also been liberalized), and even lower if compared to leading countries in energy R&D worldwide.

1.1.1. Public investment

The per capita public investment in energy R&D is below the European Union average (even EU-27), and represents only about 10% of the Japanese and 20% of the United States figures[5]. This is the case even if Spain receives significant funds from the European Union for energy R&D (in the period 2007-2010 it was the second country that received the most funding for this purpose, only after Germany).

Moreover, a significant part of the Spanish public investment in R&D is of a financial nature, consisting of loans and repayable advances. While these instruments have some advantages, as the greater commitment they require from the companies involved, they also present some challenges. The first challenge is that they distort the statistics, which usually reflect the total funds and not actual expenditure (the differential of the subsidized interest rate). The second problem is that this type of support is not well received by the companies, due to the limited amount of the subsidy and to the greater responsibility that it involves. In Spain in recent years (2009-2011) a significant portion of the public budget for innovation has not been spent (43% in 2011). This may be due

[5] Data from IEA Data Services.

precisely to financial support instruments that get rejected by the potential recipients. The third challenge is that the type of projects that companies are willing to finance with loans instead of grants will be less risky, and therefore only incremental innovation is likely to be funded.

One reason for this lack of investment in innovation could be the lack of popularity of science and the lack of scientific knowledge among Spanish society in general, at least in comparison to other countries. In fact it is surprising that, given the importance attached to energy in many issues (e.g., impact of electricity tariff hikes in the media, how much energy costs mean in families' budgets, or its impact on the CPI), most of society remains unaware of the underlying reasons and the consequences that innovation could bring about in the energy field. The fact that Spain spends less than 1% of the total energy bill in energy R&D appears revealing.

1.1.2. Private investment

Another notable aspect of energy innovation in Spain is the large participation of public investment, or alternatively, the low participation of private investment. Indeed, private investment, which is essential to stimulate technology transfer to markets and to society, and is in a better position to identify interesting opportunities for investment, is particularly low in Spain. This is not only harmful because of the untapped possible benefits of innovation mentioned above, but also because excessive dependence on the public sector exposes innovation investments to greater fluctuations, as has been the case in Spain in recent years of economic crisis (we can see how Spanish public investment in R&D has decreased significantly in the period 20010-2012: in 2012 it was 34% lower than in 2009). In fact, the public sector should serve to stabilize this type of investment, particularly in times of crisis in which some companies may have greater difficulty investing in long-term projects.

In Spain, energy companies spend less in R&D than companies in other sectors (measured as the percentage of turnover invested in R&D). Even in the clean-tech sector, for which there is significant private contribution to R&D investment at the European level, the private contribution in Spain does not exceed 30%. It is interesting to contrast this with the hypothesis advanced by Menanteau et al. (2003) that premiums to renewable technologies stimulate private investment in R&D. According to this hypothesis, Spain should have significant private R&D activity in wind and solar, and indeed there is greater patent activity in those renewable technologies supported by means of premiums. Besides, Spain exports wind technology, but imports more solar technology than it exports. However, the R&D intensity of wind and solar is between 2% and 4% (worldwide, data not available for Spain), higher than in the energy sector as a whole, but lower than in other innovative sectors such as biotechnology or ICT. This is possibly due to the fact that technologies in wind and solar sectors are gradually becoming "commodities", something that is clearly not happening in distinctly innovative sectors, such as the sector of biotechnology applied to health, which deliver new functionalities.

In the electricity sector, Spanish companies do have a certain degree of investment in innovation, although again lower than that in other countries. As expected, incumbent utilities, such as electricity and oil companies, are not the ones playing the dominant role, as they may lose from a disruptive innovation. In this regard, it is worth noting that the available data only include the R&D carried out by traditional companies in the energy sector (electricity, oil and mining, and equipment manufacturers) and that other companies that can also be considered as part of the energy sector, such as those in the wind business or in biotechnology for biofuel production, probably invest more in R&D than the traditional companies do.

Despite the low levels of private investment, most of the R&D is performed in private firms. On the one hand, this is positive, because it means having innovation activity directly connected with the productive sector. In fact, a high percentage of Spanish companies (greater than in other sectors) has introduced innovative products and processes: up to 80% of Spanish energy companies report incorporating innovations on a continuous basis over time. Moreover, the regions that have more innovative companies are the ones in which innovation efforts and policies have been more linked to the production process. However, if the R&D conducted in companies does not translate into visible, transferrable and public results, the implication could be that public funds get transferred to the private sector under the guise of innovation. In this case, the risk of free-riding and of poor effectiveness in the use of public funds is evident.

1.1.3. Technology choices

A large percentage of public investment in energy R&D is assigned to renewable technologies (even when total public investment in energy R&D is comparatively low in Spain, both in absolute and per capita terms, the fraction of that budget devoted to renewables is greater in Spain than in other countries): in relative terms, it represents more than twice that percentage in Germany, and six times more than that percentage in the United States. However, in order to be leaders in a technology, what matters most is the absolute level of public investment (assuming comparable implementation efficacy across countries) and here Spain is well below other countries. This fact is not likely to change given the relatively small size of the Spanish economy in the global context.

The very low levels of investment in innovation related to energy efficiency are particularly striking since this is an element that should have high priority in Spanish energy policy [6]. The high levels of investment on nuclear technology (only surpassed in recent years by the expenditure in all renewable technologies), even when the future prospects for this technology are not particularly bright in terms of social acceptance (e.g. WWF/Adena, 2011), is also worth noting.

1.2. Scientific publications and patents

A symptom or consequence of the lack of private investment is that, although there has been an improvement in the number of scientific publications in the energy field in recent years (2006-2010; especially in areas such as hydrogen, biomass and biofuels, or fuel cells), the number of patents is still very low compared to other countries: for example, even when patenting has increased in recent years (1999-2008), especially in renewables and biofuels, the number of patents produced per capita in Spain has only been 10% of the per capita patents in Denmark. It is true that patents themselves are not perfect measures of innovation, and in some cases they are only used as a weapon for trade war, but Spain's poor performance in the number of patents is likely to result in low income (in terms of GDP) derived from licensing, and also in low shares of high technology to trade balance.

Within this gloomy picture, and as has been already suggested, some technologies are in a better position. Thus, within the Spanish limited production of innovation, the clean-tech sector performs significantly well and constitutes a very relevant area in the Spanish innovation system. For example, Spain produces 3% of the world total patents related to renewable energy (a percentage beyond the contribution of the Spanish economy to global GDP, which is about 2%).

1.3. Human capital, infrastructure and entrepreneurial culture

Spain seems to be in an intermediate position regarding human resources for technological innovation. Innovation in energy technologies often requires technical knowledge from engineers and scientists. Spain has a significant number of graduates in engineering and sciences in per capita terms: less than Germany, but similar to Sweden and well above the United States. The problem is that the number of graduates in these

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[6] See for instance reports by *Economics for Energy* on energy intensity and economic assessment of energy efficiency measures for Spain, available at www.eforenergy.org/en/publicaciones.php

disciplines is not a good indicator of innovation capacity. First, because what matters is not only the quantity but also the quality: it may be the case that technical training in Spain focuses on solving problems with known techniques rather than on developing new techniques. On the one hand, the problem of the lack of engineering and science graduates can be solved by importing foreign trained personnel. On the other hand, Spain has, by far, fewer researchers than many other countries (in per capita terms). Obviously, this can be both a cause and a consequence of the problem (as there is little innovation activity, few people are hired to work on it). Even so, it is noteworthy that Spain has highly qualified and internationally recognized teams in some fields of study, though they are generally limited to the academic sphere.

Spain also has a rather positive situation regarding the research infrastructure. There are many publicly-owned energy research centers, although seemingly with poor coordination among them, as many of them respond to territorial interests, which limits their potential contribution to the overall Spanish innovation system. In addition, these centers often give priority to incremental innovation, and not disruptive innovation.

Another important factor worth mentioning is the low entrepreneurial culture of Spanish society. In Spain, few people engage in entrepreneurial opportunities[7], both inside and outside the workplace. Moreover, the social status of entrepreneurs is relatively low. As a consequence, the incentive to start new businesses is much lower in Spain than in neighboring countries.

1.4. Technology production

We can say that in some areas (mainly those related to renewable energies), Spain is developing some internationally competitive technology. However, in general terms and in view of this analysis, it is difficult to attribute this to the existence of good conditions for innovation, but rather it could be attributed to the individual efforts of some agents. In the case of renewables, the favorable environment that allowed some companies to invest in R&D part of the income derived from premiums to renewables can also have played an important role, together with the support of some regions to industrial development in this area.

In particular, R&D and deployment subsidies since the 1990s are likely to have contributed to a flourishing wind energy industry with relevant innovation activity.

[7] According to the Global Entrepreneurship Monitor for 2010, both the perceived opportunities for entrepreneurship and the intention of becoming an entrepreneur are considerably lower in Spain than in other countries like Germany, France, Sweden, the United States or Israel.

However, the support to other renewable technologies has not resulted in a similarly competitive industry: it is particularly paradigmatic the case of the solar photovoltaic industry, which has basically been dismantled even if relevant players existed in Spain before the introduction of premiums to renewables.

This seemingly paradoxical situation is repeated in other fields: the regions that perform the best are not the ones that have the largest budget or the most researchers. Creating a productive innovation ecosystem depends not only on how much money is put on the table, but also on the set of measures implemented, on their design and coordination.

1.5. Overview of indicators in comparison with EU and US

In order to provide an overview of the performance of the Spanish energy innovation system in an international context, Table 2 shows a summary of indicators of different inputs and outputs of the energy innovation process for Spain, the European Union and the United States.

Table 2: Summary of energy innovation indicators; comparison Spain-EU-US

	Spain	EU	US	Source and time scope
Weight of energy area in public budget for R&D	3.4%	4.1%	1.7%	Eurostat Average 2007-2010
Public investment per capita per year in energy R&D	6.28 €	8.78 €	6.00 €	
Public investment per capita per year in energy R&D [8]	1.6 €	8.9 €	12.6 €	IEA Average 2005-2011
Weight of the energy area in total number of publications	1%	0.73%		(Fundación General CSIC, 2012)
PCT patent applications per million inhabitants	2.5	6.5	6.2	OECD Year 2007
Weight of energy technologies for emissions reduction in total number of PCT patent applications	7.3%	6.4%	3.8%	
Patent and licensing revenues from abroad as % GDP (all areas, not just	0.07%	0.21%	0.64%	European Commission -

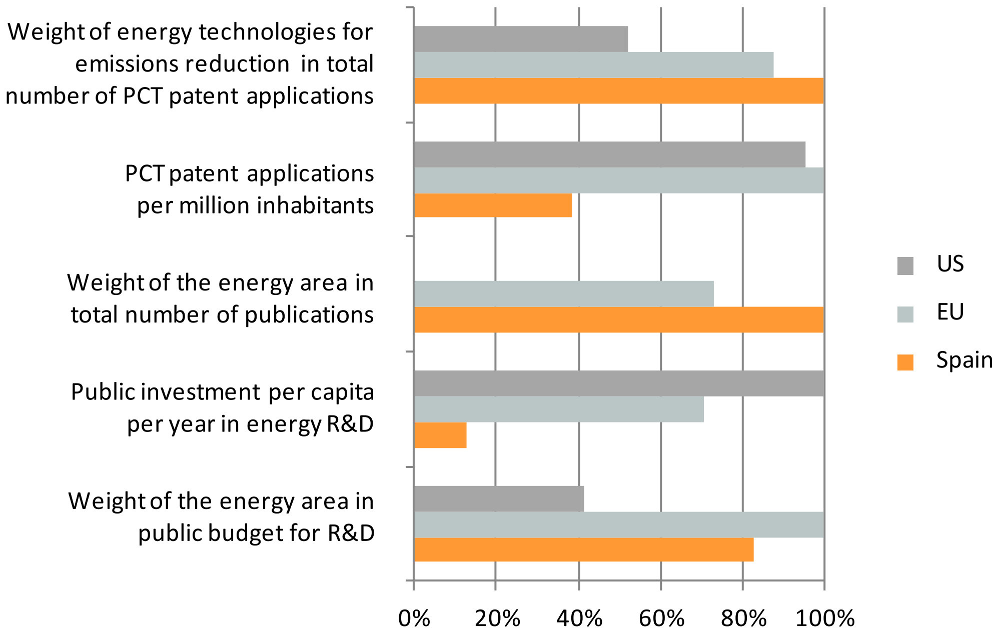
[8] This in indicator and the indicator in the previous row are equivalent, but they provide data from different sources. Note the large differences in the data for public R&D investment between IEA and Eurostat sources.

energy)				*Innovation Union Competitiveness report.* Year 2009
Contribution of high-tech to the trade balance (all areas, not just energy)	0.3%	5.1%	5.4%	

Source: Own elaboration with data from various sources

Figure 1 presents this comparison visually, transforming the values of the above indicators into percentages with respect to the maximum value among the three countries / regions considered.

Figure 1: Summary of energy innovation indicators; comparison Spain-EU-US



Source: Own elaboration with data from various sources

The evidence presented in this section suggests that there is much room to improve the performance of Spain's energy innovation system. Furthermore, evidence from other countries indicates that, by failing to stimulate more innovation in the energy sector, Spain may be missing significant savings in the energy system, along with other benefits for the overall economy. Section 2 provides an evaluation of the returns of R&D investment in terms of cost reductions in the energy system for the Spanish case.

2. What benefits can we expect from energy innovation?

The purpose of this section is to present the assessment of savings that could be achieved in the Spanish energy system if R&D in energy technologies increased. The analysis does not include investment in other policies that could also contribute to innovation understood in a broader sense, such premiums, loans, standards, etc.

Before presenting the analysis, it is important to stress that only savings in terms of reduced cost of energy technologies are quantified here. Other benefits such as domestic value creation, increased competitiveness, environmental benefits, etc., have not been assessed.

2.1. Case study definition and methodology

The case study focuses in the Spanish energy system in 2030. The aim is to assess the potential savings that the Spanish energy system could realize in several scenarios of R&D investment at the European level for various energy technologies. The technologies considered are solar photovoltaic (PV), concentrated solar power (CSP), wind, CO_2 capture and sequestration (CCS), nuclear, gas, batteries (for electric vehicles (EV) and plug-in hybrids (PHEV)) and biofuels.

When defining the scenarios of R&D investment, we consider annual public investment levels in energy R&D in the European Union as a whole. It is important to notice here that, for the purpose of this study, it is not relevant where the funds come from, nor where they get executed. This is because we will estimate benefits for Spain as "taker" of technological improvements, whereas other potential benefits as "maker" will not be considered (e.g. improved industrial fabric, income from exporting technology, etc.). Regardless of which countries invest in R&D, if reductions in the cost of energy technologies get realized, then savings in the Spanish energy system can be realized as well.

To evaluate the savings that reducing the cost of technologies could mean for the energy supply in Spain, we have used the model of the Spanish energy system developed by López-Peña et al. (2011). It is a bottom-up partial-equilibrium model of the whole Spanish energy sector (including electricity, transportation, heat and industrial uses). The model describes all major energy processes, from primary energy production (domestic or imported), through conversion and transport of energy (oil refining, gasification, power generation, transmission and distribution, etc.), to final energy consumption in all sectors (residential, industrial, primary, services, and transportation).

With this model, we estimated the total cost of the Spanish energy system in 2030 given certain reductions in the cost of technologies in different scenarios of R&D investment. As a base case, we consider the scenario in which the annual investment in R&D is maintained at current levels until 2030. From the model results, we can calculate the potential annual savings as the difference between the cost of the system in different scenarios of investment in R&D and the base case. We also estimate the returns by dividing the annual savings by the increase in annual investment in R&D required for achieving them.

For the analysis, CO_2 emissions throughout the Spanish energy system will be limited to an annual maximum of 164 Mt in 2030, which would mean a reduction of 20% compared to 1990 emissions (in line with the objectives of the European Union for 2020). In our baseline scenario, we assume that no new nuclear plants will be installed, because their construction would have to begin in the coming years if they were to be operative in 2030, and this does not seem realistic in view of the current climate. However, we will perform a sensitivity analysis to evaluate how the results would vary if the installation of new nuclear power plants was allowed.

2.2. Data

The data used for this analysis on how future technology costs may be affected by R&D investment comes from two projects: the ICARUS project in Europe[9], and the ERD3 project in the US[10]. Both projects carried out expert elicitations on the future cost of energy technologies based on the level of public investment in R&D and for a time horizon set in 2030. Experts came from various sectors: private, academic, and government. They also captured the uncertainty associated with these estimates by asking the experts for a range of possible costs expressed as percentiles 10, 50 and 90. The technologies discussed were PV, CSP, biofuels, batteries (for EV and for PHEV), nuclear, gas and CCS.

When building the scenarios of R&D investment, the two projects took a different approach. The ICARUS project considered three scenarios of R&D investment: one in which R&D investment remains at current level ("current"), one in which R&D investment increases by 50% with respect to current levels ("current +50%"), and one in which R&D investment increases by 100% ("current +100%"). On the other hand, the

[9]http://www.icarus-project.org. Fondazione Eni Enrico Mattei.

[10]http://belfercenter.ksg.harvard.edu/project/10/energy_technology_innovation_policy.html?page_id=213. Belfer Center for Science and International Affairs (Harvard Kennedy School).

ERD3 project asked the experts which their recommended level of R&D investment would be, and then considered the "current" scenario plus three other scenarios based on that recommended level of R&D investment: one in which R&D investment equals their recommended level ("recommended x1"), one in which R&D investment is half their recommended level ("recommended x0.5"), and one in which R&D investment is ten times their recommended level ("recommended x10").

Table 3 collects all the estimates of cost reductions for the different technologies and scenarios of R&D investment. In order to consider the uncertainty inherent in the innovation process, for each technology and scenario, we consider the most pessimistic estimate (or, in other words, the one of minimum cost reduction, which will be included as "min" in the table that summarizes the data we have used), the most optimistic estimate (of maximum cost reduction, "max" in the table), and an intermediate estimate (the median of the estimates of cost reduction, "med" in the table), among all the percentage savings calculated from expert estimates for percentiles 10, 50 and 90. For improving the representation in the most probable range of cost reduction, we also consider the minimum, median and maximum savings among the experts' "best guesses" (percentile 50).

Table 3: Input data: scenarios of cost reductions in energy technologies in 2030 depending on the level of public R&D investment

Technology	R&D investment scenario	Percentiles 10, 50, 90 min	med	max	Percentile 50 ("Best guess") min	med	max	Reference	Method, project
PV	current +50%	0%	16%	50%	0%	16%	37%	(Bosetti et al., 2012)	Expert elicitation, ICARUS Project for EU
	+100%	0%	32%	83%	0%	31%	64%		
CSP	current +50%	0%	10%	17%	5%	13%	17%		
	+100%	2%	19%	57%	10%	19%	33%		
Biofuels	current +50%	0%	13%	38%	0%	13%	29%	(Fiorese et al., 2012)	
	+100%	0%	25%	67%	0%	25%	57%		
Batteries > EV	current +50%	0%	10%	50%	0%	10%	33%	(Bosetti et al., 2011b)	
	+100%	0%	22%	75%	0%	17%	60%		
> PHEV	current +50%	0%	10%	50%	0%	9%	32%		
	+100%	0%	20%	67%	0%	16%	59%		
Nuclear	recom.x0,5	0%	0%	14%	0%	0%	8%	(Anadon et al., 2012)	
	x1	0%	8%	21%	0%	8%	17%		
	x10	0%	17%	25%	5%	20%	25%		
Gas	recom.x0,5	0%	0%	40%	0%	0%	40%	(Chan et al., 2010)	Expert elicitation; ERD3 Project for US
	x1	0%	0%	52%	0%	8%	52%		
	x10	0%	7%	66%	0%	16%	66%		
CCS	recom.x0,5	0%	0%	6%	0%	0%	0%		
> coal power	x1	0%	4%	20%	0%	9%	20%		

plants	x10	0%	18%	40%	3%	20%	40%		
> gas power plants	recom.x0,5	0%	0%	50%	0%	0%	50%		
	x1	0%	4%	60%	0%	10%	60%		
	x10	0%	18%	67%	5%	20%	67%		
Wind	current +50%					8%		(Klaassen et al., 2005)	Learning rates, data from EU
	+100%					11%			

Note that, since we had no available data from expert elicitation for wind technology, we resorted to data from two-factor learning curves in order to estimate the cost savings associated with R&D investments. Even if this approach has well-known limitations (Qiu and Anadon, 2012), we found useful to use these estimates to get an order of magnitude of the benefits associated with wind technology, as this technology is becoming increasingly important in the Spanish energy system.

The levels of R&D investment considered to build the scenarios of R&D investment for each technology can be found in Table 4.

Table 4: Scenarios of annual public R&D investment in energy technologies in the EU

	R&D investment [€ million]	
Technology	current[11]	recommended[12]
PV	163	
CSP	38	
Biofuels	78	
Batteries	100	
Nuclear	702	1500
Gas	18	162
CCS	56	477
Wind	92	

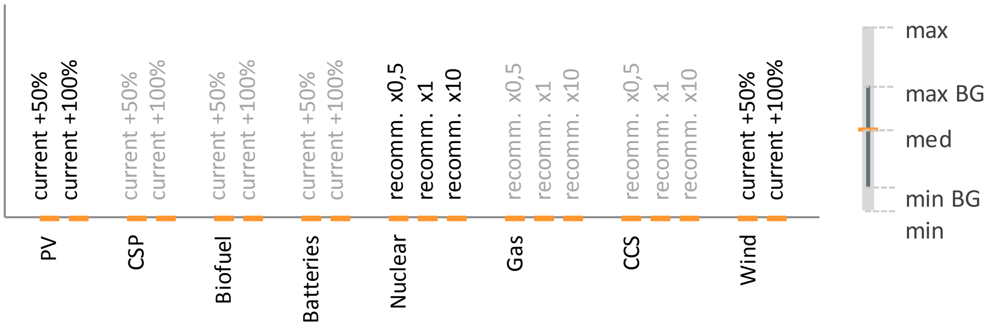
2.3. Results

To present the results in a condensed form, we will present some graphs showing savings and returns for all technologies and R&D scenarios, including a representation of the range of uncertainty of the results. Figure 2 works as a legend to understand these graphs.

[11] Based on data of public investment in R&D in technologies of the EU SET Plan in 2007 (Wiesenthal et al., 2012b); (Wiesenthal et al., 2011) for batteries.

[12] Median of levels of R&D investment recommended by experts. For nuclear, we used estimates for the EU (ICARUS Project). For gas and CCS, we used estimates of R&D investment in fossil fuels and CCS (all together) in the US (ERD3 Project), and then applied the corresponding share for gas and CCS based on data in (Chan et al., 2010).

Figure 2: Legend to understand the figures of results



On the left side of the figure, we can see how technologies and scenarios will be organized in the graphs: the first four technologies have two columns of results each, corresponding to scenarios "current +50%" and "current +100%" respectively (this will be the case also for wind technology, placed separately as the last technology just to emphasize we have used different type of data, as data from expert elicitation was not available); the next three technologies have three columns of results each, corresponding to scenarios "recommended x0.5", "recommended x1" and "recommended x10".

On the right side of the figure, we can see how uncertainty will be represented: the horizontal orange line indicates the result for the median cost reduction; the wider light grey column represents the range between the result for the minimum cost reduction and the result for the maximum cost reduction among all estimates (considering percentiles 10, 50 and 90); analogously, the vertical dark grey line represents the range between the result for minimum cost reduction and the result for maximum cost reduction but only among the "best-guess" estimates (BG, those in percentile 50), which allows for providing greater detail in the most probable range of results.

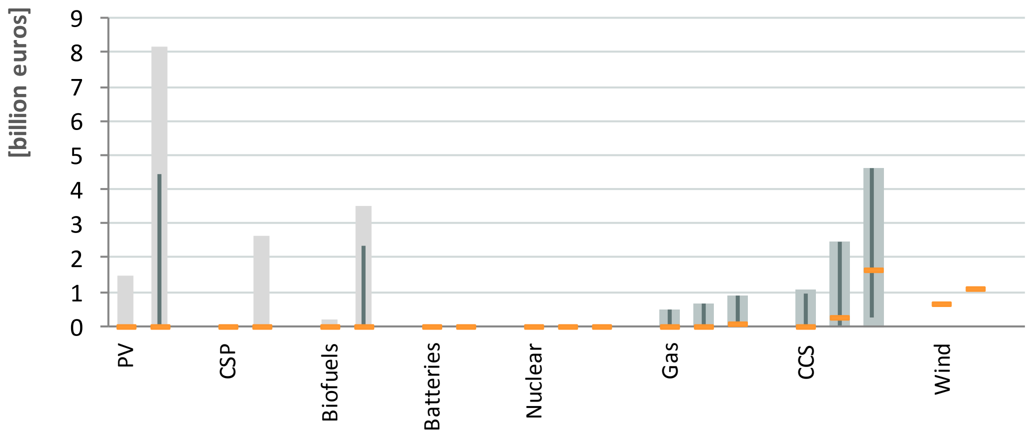
2.3.1. Savings

As already mentioned, savings are calculated as the reduction in the cost of the Spanish energy system in 2030 for a scenario in which R&D investments increase with respect to current levels, as compared to an scenario business-as-usual in which R&D investments are maintained at current levels. Figure 3 represents the savings obtained for different technologies and scenarios of R&D investment[13]. The total cost of the system, with respect to which the savings are calculated represents 113 billion euros (considering costs

[13] It should be noticed that, although the savings are presented by type of technology, they depend on the investment portfolio including other technologies, as some of these technologies would compete in the market.

of investment in new capacity, operation and maintenance costs, transportation costs, etc. for the entire Spanish energy system in 2030).

Figure 3: Savings in the Spanish energy system in 2030 due to reductions in the cost of technologies thanks to R&D investment (without new nuclear capacity)



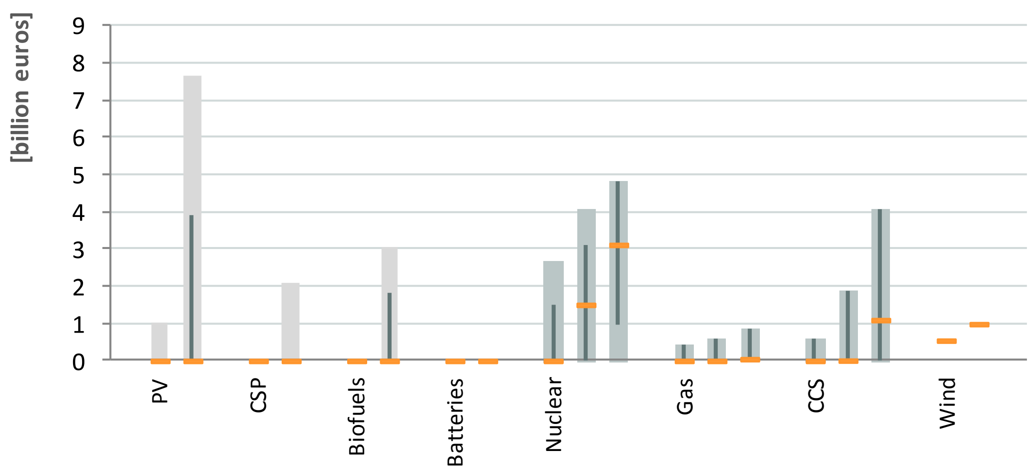
A first observation is that for most of the technologies and scenarios of R&D investment considered there are no savings for the median estimate of cost reduction (i.e. horizontal orange marks are at zero). What is happening in these cases is that no new capacity of the corresponding technology is being installed, since it is less cost competitive than other technologies. In particular, in the baseline case in which CO_2 emissions are limited to 80% of the emissions Spain had in 1990, the need of new installed capacity is mostly being covered with wind, gas turbines, and coal and gas power plants with CCS. Thus, we can observe how median estimates of cost reduction do lead to savings for the cases of wind and CCS. However, other technologies (PV, CSP and biofuels) need cost reductions over the median estimate in order to lead to savings for the system.

In terms of maximum achievable savings, photovoltaic technology stands out (with maximum potential savings of up to 8.000 million euros in the highest R&D investment scenario), followed by the CCS (with maximum potential savings of 4.500 million euros in the highest R&D investment scenario). Biofuels and CSP only get significant savings in the highest R&D investment scenarios (reaching almost 3.000 million euros for the maximum cost reduction estimates). Gas power plants present moderate potential savings compared to other technologies (below 1.000 million euros for all investment scenarios and even for the maximum cost reduction estimates). Savings for wind technology are in that same order of magnitude.

In the case of batteries, our results show no savings even for the maximum cost reduction estimates. The explanation to this is that, according to our results based on cost expectations of future vehicles, electric vehicles (including both EVs and PHEVs) are less cost effective than biofuel vehicles when it comes to decarbonize the transport sector. We have checked that for electric vehicles to displace biofuel vehicles in our model, the cost reduction of batteries needs to be over 75%. Given that the maximum cost reduction we have considered in our scenarios is 75% (see Table 3), electric vehicles do not get to penetrate the market in our results, and thus present zero savings or returns on R&D investment.

For nuclear technology, no savings are obtained in the baseline scenario because, as already mentioned, we are assuming no new nuclear power plants will be installed in Spain in the 2030 horizon. If we allow for the installation of new nuclear power plants, results will be as shown in Figure 4. Savings for all the technologies but nuclear become slightly lower as compared to the baseline scenario (between 100 and 600 million euros less, depending on the technology an scenario, which represents in any case less than 0.5% of the total cost of the system). For nuclear technology, significant savings are achieved (in the order of 1.500 million euros for the most probable cost reduction at the level of R&D investment recommended by experts, and up to 5.000 million euros in the scenario of maximum investment in R&D and for the highest cost reduction estimate).

Figure 4: Savings in the Spanish energy system in 2030 due to reductions in the cost of technologies thanks to R&D investment (with new nuclear capacity)



We have also assessed the sensitivity of results to changes in the price of fuels and confirmed they are robust: if the price of gas and oil increases by 35%, savings barely vary (differences represent less than 1% of the total cost of the system).

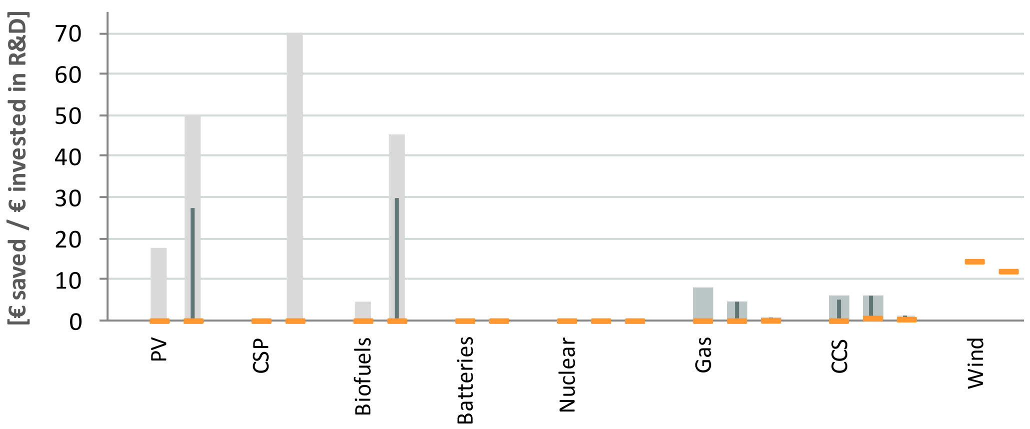
2.3.2. Returns on investment

Once savings have been estimated, we can now compare the potential savings with the level of R&D investment that they would involve. For this purpose, we calculate returns on R&D investment as the annual savings in the Spanish energy system for a given scenario of R&D investment, divided by the increase in R&D investment that that scenario involves with respect to current levels of investment.

It should be noticed here that we are considering savings for Spain but investments at the European level. This can be justified in two ways. First, as we have already explained, the purpose here is to estimate the savings that the Spanish system could realize given certain reductions in the cost of technologies, regardless of where the investment in R&D takes place. Second, if we confirm that the savings that the Spanish system could realize are greater than the required levels of R&D investment at the European level, this would mean that the return for Europe as a whole (the savings for all the Member States compared to their total investment in R&D) would be even higher, since we could expect other European countries to realize savings as well.

Figure 5 presents the obtained returns on R&D investment. The considerations that we made for savings (regarding zero results for the median estimate of cost reduction, regarding nuclear, and regarding batteries) apply for returns as well. Also the sensitivity analysis already mentioned applies to these results, since returns are obtained just by dividing savings by investments.

Figure 5: Returns to R&D investment, baseline scenario



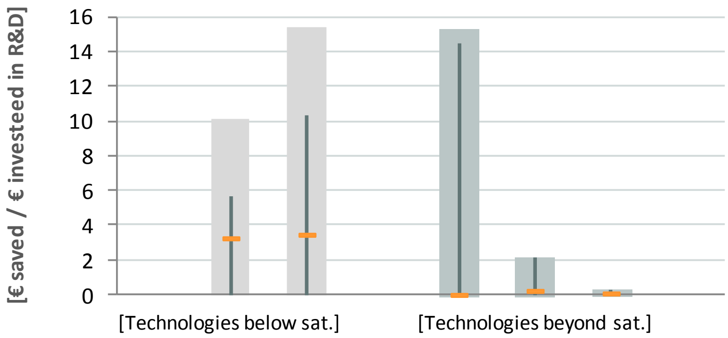
Once more, we see how for many technologies and scenarios, there is a chance no returns will be realized, since the expected reductions in technology costs (as predicted by experts from various sectors) are not sufficient to make those technologies competitive. However, when cost reductions become sufficient to make the technology cost-effective, then returns soar: potential savings can represent up to 70 times the investment. This is the case for CSP in the highest R&D investment and for the maximum cost reduction estimate (but nevertheless presents zero returns in the lowest R&D investment scenario). Photovoltaics and biofuels can also achieve very significant returns, up to 50 or 45 times the investment respectively. Returns for wind technology are around 14 times the investment. Of course, here it should be noticed that given the uncertainty about future costs, the expected return is lower than the highest possible.

Gas and CCS technologies showed returns in the order of 5 times the investment, although these returns become almost zero when R&D investment increases too much. This happens also for nuclear technology, when we allow for its installation (not represented in this figure), it achieves returns over 50 times the investment in the lowest R&D investment scenario, but its returns plunge in the high investment scenarios. These results are consistent with those obtained in a similar study for the US, in which increasing public investment in energy R&D by a factor greater than 20 did not prove beneficial (Anadon et al., 2011).

Then, we see how for some technologies increasing R&D investment leads to higher returns (that is the case of PV, CSP and biofuels), whereas for other technologies increasing R&D investment leads to lower returns, sometimes even to the point of cancelling them (that is the case of gas and CCS). This is because the reduction in the cost of a technology saturates at a certain zone, beyond which any additional investment does not lead to significant additional reduction in the cost of technology. Thus, for the first group of technologies (that provide increased returns when R&D investment increases), it seems the levels of investment that we have considered are below the saturation zone, whereas for the second group of technologies (that provide reduced returns when R&D investment increases) the levels of investment seem to be beyond the saturation zone. Indeed, this seems reasonable given that for this second group of technologies the highest investment scenario corresponds to ten times the investment recommended by experts. It should be noticed that this saturation depends on the opinion of experts consulted in 2010 and 2011. Once the level of R&D increases and the scientific knowledge advances, this estimation can possibly change (in other words, the saturation point should not be considered permanent in time).

This effect can be observed clearly in Figure 6, which presents the returns obtained when considering together all the technologies for which we have investment scenarios based on current levels of R&D investment (PV, CSP, biofuels, batteries and wind), and all the technologies for which we have scenarios based on recommended levels (nuclear, gas and CCS). We can observe how for the first group of technologies, the highest investment would yield the highest returns, whereas for the second group of technologies, the highest returns would be yielded by the lowest investment.

Figure 6: Returns on investment in R&D for groups of technologies, baseline scenario



Considering this last figure, we could conclude that if we were to invest in the portfolio composed of PV, CSP, biofuels, batteries and wind (first group of technologies), the expected returns would be in the order of three times the investment (corresponding to the median estimates of cost reduction), although returns could reach ten times the investment in the most favorable scenarios. For the portfolio composed of nuclear, gas and CCS, the maximum returns could be in the same order of magnitude (up to fifteen times the investment in the most favorable scenario), but only for the lowest level of R&D investment.

These returns are in a similar order of magnitude, although slightly more conservative, of those estimated for the US in a similar study, which were about twenty times the level of investment (in 2030, for recommended levels of R&D investment and median estimates of cost reductions) (Anadon et al., 2011).

From this analysis we can conclude that the savings that the Spanish energy system could realize due to reductions in the cost of energy technologies, thanks to R&D investment, are significant and sufficient to recuperate the investment in R&D in most cases (with a high degree of uncertainty, though). However, it is difficult to identify the most promising technologies due to the high degree of uncertainty involved. The recommendation would then be that Spain chooses the technologies in which to focus its R&D investment in the context of a European portfolio.

3. How could we improve energy innovation in Spain?

In view of the assessment presented in the previous sections, and of the available options, which should be the priorities of an energy innovation policy aiming to create national wealth?

These priorities should target various fronts. As argued previously, a successful innovation policy cannot rely only on subsidies and grants, but rather should also consider an appropriate institutional framework that covers all areas of knowledge, and that provides answers to the technological challenges of companies. There are several instruments available for this, and they should be combined to achieve the proposed objectives.

In the Spanish case, the conclusions of the assessment of the current situation and the evaluation of potential savings suggest the following priority actions to promote energy innovation:

- perform a strategic analysis of innovation priorities, of the areas in which Spain would better specialize,
- promote an increase in private investment, and also in more public-private partnerships in the execution of R&D,
- improve institutional design and promote ecosystems for innovation and entrepreneurship,
- consider carefully the coordination between energy policies and innovation policies, and incorporate incentives for innovation into the regulatory design of the energy sector,
- and improve the communication to and the education of society on the importance of energy innovation.

In this section we further develop these ideas. However, we should mention that the recommendations expressed herein are general in nature, due to the characteristics of this study. The design implementation of specific measures should be preceded by a thorough analysis of their consequences for the Spanish innovation system.

3.1. Strategic analysis of priorities

First, it is essential to perform a strategic analysis that would allow for establishing priorities in the promotion of energy innovation. Given the size of the Spanish economy, Spain cannot claim to be leader in all technologies. Moreover, given the scarcity of public funds, investing effectively requires concentrating in a particular set of technologies. At the same time, because of the uncertainty inherent in innovation, focusing on only one or two productive sectors is not advisable either. It will be necessary to choose the technologies for which Spain has some comparative advantages, in the context of a joint exercise that also defines the desired energy model and the policies that need to be implemented in order to achieve it, as well as to consider the possible implications of innovation investments for the competitiveness of the country. This exercise could benefit from the advice of experts both from academia and the business world. It may be interesting in this respect to appoint a panel of experts, much like the Energy Innovation Council proposed in the U.S. to both analyze policies and propose new measures.

When choosing technologies or priority areas, we should take into account their potential for improvement, their niche market, Spain's comparative advantages and the benefits that can be derived from them. For instance, Spain has a better starting point in some clean technologies than other countries (at least in terms of publications and patents).

The estimates presented in Section 2 reflected potential savings and returns on investment offered by different technologies, which could constitute an important input when deciding how to prioritize technologies. Even though these results depend on the model and technology assumptions, they are based on a transparent and consistent analysis. In these results, PV appears as the technology with the largest potential in terms of maximum achievable savings for the Spanish energy system (but with large uncertainty), followed by CCS (with less uncertainty). In terms of potential returns, PV stands out again, together with other technologies such as concentrated solar and biofuels, with similar levels of maximum return. CCS, however, presents more modest return levels, similar to those of gas technologies. Wind technology is in an intermediate position, ranking better in terms of potential returns than in terms of potential savings. Nuclear technology (when new nuclear plants are allowed) also shows significant potential savings (in volume terms, not per MW installed), and high returns in the lowest R&D investment scenario (but low returns in high R&D investment scenarios).

3.2. Promoting private investment

Correcting the imbalance between public investment and private investment is also essential for energy innovation in Spain. This involves both redesigning the support mechanisms and redesigning the related institutions and infrastructure. The goal should be to break the false dichotomy between public investment and private investment, in such a way that one is not used to replace the other, but rather that both act in parallel, complementing each other. Except for basic research, the role of public investment should not be just funding what private investment fails to fund, but instead public and private investment should act in concert to strengthen the prioritized areas of research and technologies, and thus be able to achieve the above-mentioned technological leadership with the corresponding value creation.

Of course, within this coordination between the public and the private sectors, the private sector should play a more active role, given the generally applied nature of energy technology. This does not mean that funding for basic science should be reduced.

Instead, Spain could experiment with the creation of targeted institutions, such as the Energy Frontier Research Centers created in the U.S., in which some resources are focused in those areas of basic science that have the greatest potential to contribute to technological advances in areas such as energy, nanomaterials for energy efficiency applications, electrocatalysis for applications in biofuels and energy storage, systems far from equilibrium for conductivity applications, superconductivity, energy storage, to name just a few. These centers have more stable funding, promote multidisciplinarity and have a critical mass of researchers.

Another problem of many funding programs for applied research is that companies do not collect information on the short- and long-term results, therefore making it difficult to design programs that would benefit from previous mistakes or experiences. Thus, support mechanisms should focus on evaluating the results of the projects and, in many cases, depending on the results of these assessments, focus on gradually adding new support mechanisms to the usual instruments in the form of grants (direct or financial). For instance, although grants are recommended for basic research, they may be unsuitable for business and applied research because of the difficulty of ensuring their efficient use and the dissemination of the results. In some cases it may be desirable to introduce other types of incentives, such as prizes, which are open and competitive, to reward results and not mere spending, and to attract different types of inventors and entrepreneurs, who may produce more disruptive inventions, and thus generate added value for society. Another instrument under the induced innovation framework would be to use price signals. In this case, it is essential to keep price signals stable in the long-term and to allow the participation of private investors.

In any case, the instruments used must be properly fitted to the characteristics of the technology or the desired innovation, mainly related to the position of the technology in the learning curve. Less developed technologies should rely more on direct support policies, while those technologies already in a commercial phase could benefit from induced innovation policies, and demonstration projects should be supported by public-private partnerships.

The creation of markets and business opportunities can also contribute to the mobilization of the private sector. Of course, these markets should have the appropriate level of competition to optimize innovation investments. It is generally considered that too low or too high competition discourages innovation. On the one hand, excessive competition forces companies to cut costs in the short term; on the other hand, the lack of competition, while it generates rents that could be invested in innovation, it removes the incentives to do so. A possible compromise (albeit with many complexities of design) is that the State provides such funds that would be available to a monopolist, but that companies compete for the funds in a real market. This is not without problems, of course: in a competitive environment, how can we ensure that the results of innovation provide benefits for society?

3.3. Institutional design, innovation ecosystem and entrepreneurship

Related to this last issue, and now moving into the realm of the third line of action we mentioned, the promotion of innovation also requires establishing an inclusive institutional design (as defined by Acemoglu and Robinson) that provides enough reward for innovators and entrepreneurs, and prevents rent extractors from stifling innovation in which they do not have a stake.

As already mentioned, the evaluation processes and the accountability of those agents participating in the innovation system and receiving public funding should be improved. This would create the opportunity to learn and improve the effectiveness of the funding system. Although obviously the innovation process is inherently uncertain, and some of the expected results may not get realized, it is possible to demand more accountability, traceability and transparency in the use of public resources. The aims would be to identify both new areas of interest and the most efficient funding mechanisms for different purposes and technologies.

The role of structures and facilities can also be the key to improve the environment for energy innovation. The creation of an agency like ARPA-E in the U.S., run by people with an entrepreneurial spirit, specializing in risky innovations, and supporting energy start-ups, could contribute much to the rather conservative current structure. It also seems appropriate to create virtual structures, centers of excellence, in line with the idea of prioritizing as already mentioned. These centers could operate similarly to the Energy Innovation Hubs in the U.S., focusing the efforts of individual research centers, universities, and of course private companies on the technology or innovation lines identified as priorities. The model followed by the Basque Country also provides an interesting reference, as does the newly created International Energy Research Centre (IERC), a research center led by industry, funded by government, and in direct collaboration with university, which aims to achieve commercial innovations in the energy field. These centers often engage in international collaboration with the technology leaders of the future (no matter where they are located -Europe, United States, China or Brazil).

Not only is it important to create leading centers in priority technologies, it is also important to create the right environment and relationships so that innovation can emerge from below, as the result of collaboration between various stakeholders. The case of wind technology in Denmark, where networks of cooperation and communication between industry and interest groups (largely motivated by a suitable design of incentives) played a key role in developing successful wind energy technology is also interesting. Industrial clusters (defined as a concentration of companies of a specific sector in a particular geographic area, interconnected collaboratively among them and with suppliers and local institutions, and generally characterized by strong social roots in their region) can also play a key role in the development of energy technologies, as the case of the wind energy cluster in the Basque Country demonstrates.

To complete the innovation ecosystem, we should also encourage entrepreneurship and promote the funding sources that make it possible. Entrepreneurs can play a key role in generating disruptive innovations and ideas that can really challenge the status quo. They also have the ability to enhance the productive industrial network, generate employment and add value. The case of Israel is particularly noticeable as a model of an entrepreneurial ecosystem. Israel is now one of the world leaders in clean-tech start-ups, despite not having an energy policy that promotes these technologies, and thanks to a large extent to the exceptional mobilization of private seed capital. It is important to note that investor capital in Israel, which nowadays is one of the highest in the world, was initially boosted by a government program (the Yozma program, introduced in the early 90s), and also that the defense activities of Israel have contributed to a very competitive technology sector.

Indeed, we should not forget that the government could play a key role as facilitator and promoter of all the ideas mentioned about the institutional design and the creation of productive innovation ecosystems: by establishing the right incentives, supporting with public funds the initiatives that require it, creating adequate and purposive institutions, encouraging collaboration among institutions, disseminating information, building networks, promoting a favorable investment climate, etc.

3.4. Coordination with energy policy and attention to regulatory design

Energy innovation policies should be aligned with more general energy policies. This idea has already been advanced in part when we mentioned the need to combine and coordinate technology-push policies and demand-pull policies. Energy policies may serve to guide investments in energy innovation thereby serving as market pull policies. Incentives for renewable installation are a clear example of this: the decision to promote the installation of renewables spurs the market for renewable technologies, and promotes innovation in the sector. Another example is the introduction of a market for CO_2 emissions: if the price of CO_2 becomes sufficiently high, it will provide an incentive to invest in innovation in low carbon technologies.

The literature shows that both market pull and push polices are needed. For example, considering again the case of renewables, it is striking how the large subsidies that Spain has devoted to photovoltaics have not resulted in significant innovations in the sector inside the country. It is possible that if those subsidies had been complemented with policies that had directly supported innovation (technology-push), the results might have been more favorable. Some ideas that might have been considered then, and could be considered in the future are (many related to lines of action already mentioned): we could prioritize public investment in R&D on technologies that are being promoted in the general energy policy framework; we could create centers of excellence in these technologies to integrate and coordinate all the related R&D activities developed in the country; or we could open channels of communication and establish collaborative networks among research groups, investors, installers, operators and manufacturers of the technology in the country, so that the knowledge generated in the installation and operation phases can provide feedback to the research and development phases.

Finally, it is important to highlight the potential importance of regulation in the energy sector in limiting or promoting innovation, most notably in the electricity sector. While in most sectors the expectations of rewards from innovation depend directly on market conditions, in the electricity sector they depend significantly on regulatory conditions. The clearest example is perhaps the case of the regulated activities of transmission and distribution of electricity, whose remuneration depends on a regulated tariff. To encourage innovation in these activities, it would be necessary to introduce incentives for innovation in its remuneration scheme (as intended in the RIIO compensation scheme proposed in the U.K.). In order to promote innovation in power generation, besides improving market creation policies, regulation could facilitate the entry of new players, for instance, by removing barriers to the connection of distributed generation, which could be a fertile ground for innovation. On the demand side, there are entry barriers for new potentially innovative agents (ESCOs, aggregators, or start-ups for demand management), that regulation could help to overcome.

3.5. Education and communication

First, the lack of scientific knowledge about energy and its environmental and economic implications suggests the need to make communication and education efforts convey the importance and possible benefits of investing in energy innovation to society. We must take this message to the media, and also present related scientific analysis in the major social and political debates.

Second, it is essential to promote an entrepreneurial culture in schools and universities. An entrepreneurial culture is key to creating companies that innovate in the energy sector, and that will create value for the Spanish economy.

Finally, regarding communication, we must also try to strengthen the dissemination of the innovation results, and to facilitate their transfer to the productive sector, in such a way that the innovation results reach companies beyond those where publicly funded innovation takes place.

In a context where innovation is increasingly essential as part of the economic policy of a country, as a factor of competitiveness, the government should carefully consider those options that would allow moving towards a more secure, environmentally friendly and competitive energy model. However, as already mentioned, defining specific policies would require further analysis of these recommendations, based on empirical data, so that the most appropriate design can be defined and its performance and expectations assessed.

4. Synthesis and research question

The conclusions from the analysis about energy innovation in Spain that we have presented in this chapter are not very positive. Two main reasons can be identified: first, the low volume of investment, particularly of private investment; and second, the lack of a robust innovation ecosystem. More specifically, the main shortcomings identified for the Spanish energy innovation system are:

- low absolute level of investment in energy innovation (and a large part of it is channeled as loans, which does not seem appropriate),
- low contribution of private investment,
- low innovation production, particularly in terms of patents and exports (not that low in terms of publications),
- low popularity and scientific knowledge about energy in Spanish society,
- low entrepreneurial culture.

The benefits that could be realized from spurring energy innovation seem to be significant. Our analysis has shown how, only in terms of savings in the energy system as a result of cost reductions in energy technologies thanks to R&D, the expected benefits could reach more than fifty times the R&D investment for some technologies (although with a high degree of uncertainty). To the savings that could be realized in the energy system, we should add all the socioeconomic benefits that innovation could bring about in terms of new businesses, employment, improved capabilities, etc.

It then seems urgent to strengthen and redirect investment in energy innovation, and foster private investment, creating an environment that promotes innovation in an entrepreneurial environment. The priority actions identified in this assessment to achieve these objectives are:

- perform a strategic analysis of the innovation priorities, of the areas in which Spain should specialize,
- increase private investment, and promote public-private partnerships for executing R&D,
- improve the institutional framework and promote innovation and entrepreneurship ecosystems,
- coordinate innovation policy with energy policy, and consider how the regulatory design of the energy sector could facilitate innovation,
- and raise public awareness of the importance of energy innovation through communication and education to society.

Of all these recommendations, there is one that we find particularly intriguing: the first one on the need to "perform a strategic analysis of the innovation priorities". How could such an analysis be made? Are there frameworks that could provide some basis for it? And what exactly being strategic would mean in the context of energy innovation policy? All these questions will guide the literature review presented in the following chapter, Chapter 3.

Based on this need for strategic energy innovation policy, and coming back to the introductory discussion in Chapter 1 on how energy innovation is crucial to respond to sustainability challenges and how it could provide an opportunity to generate welfare for countries, we are ready to specify the overall research question this thesis aims to tackle. It could be condensed in few words as follows:

> **How could countries undertake energy innovation policy more strategically*?**
> *in such a way that innovation efforts can be directed effectively
> to advance towards more sustainable energy systems
> and realize welfare-improving benefits

Chapter 3_

Literature review

The need for a framework to make sense of innovation policy in a globalized context

Literature review.
The need for a framework to make sense of innovation policy in a globalized context

In the previous chapter, Chapter 2, we came to specify the research question for this thesis in the following way: *How could countries undertake energy innovation policy more strategically? - in such a way that innovation efforts can be directed effectively to advance towards more sustainable energy systems and realize welfare-improving benefits*.

In this chapter, Chapter 3, we will begin by reflecting on what 'strategically' actually means and on how the concept of strategy can be applied in the context of energy innovation policy, highlighting the implications of sustainability and globalization (Section 1). We will then review the literature to discover how different disciplines have provided different perspectives on innovation processes and different frameworks to analyze them (Section 2). Finally, we assess the potential of these frameworks to facilitate strategic thinking for energy innovation policy and identify the research gap (Section 3).

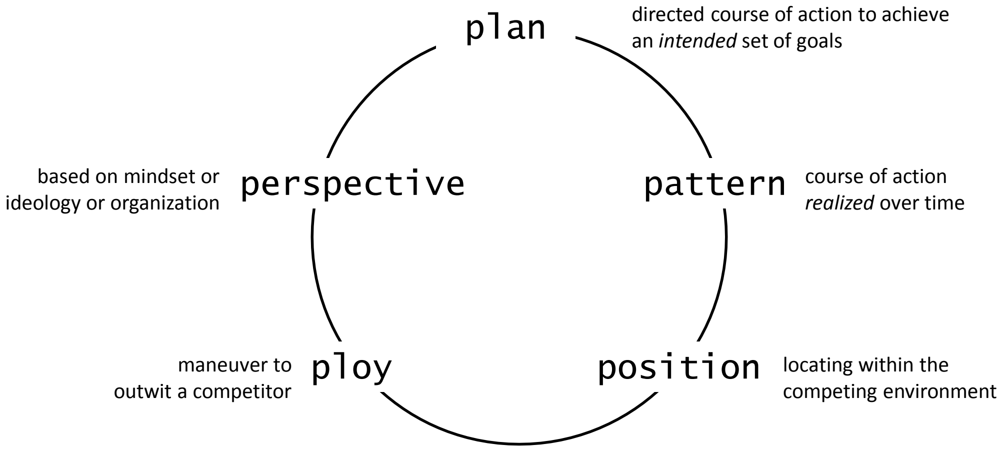
1. Preliminary reflections on 'strategy' and the implications of globalization

1.1. What is strategy?

Traditionally, the term strategy has referred to some sort of plan to achieve certain goals, and has been studied in fields as diverse as the military, game theory and management. We will focus here on the interpretations given in the management literature, where much work on strategy has been developed, on the intuition (argued later) that the insights from this field of study may be of some application in the context of policy-making.

When looking for a definition of the term strategy in the field of strategic management, we find there is no single, widely-accepted definition. Some even suggest that the search for a single definition is futile, and instead we should put our efforts in understanding the multiple interpretations and variations of what strategy may mean in different contexts and organizations (Mintzberg, 1987a). Indeed, Mintzberg suggests at least five interpretations are possible (the "five Ps for strategy"): strategy as a plan, as pattern, as position, as ploy and as perspective -see Figure 7 for a hint on what characterizes each of them.

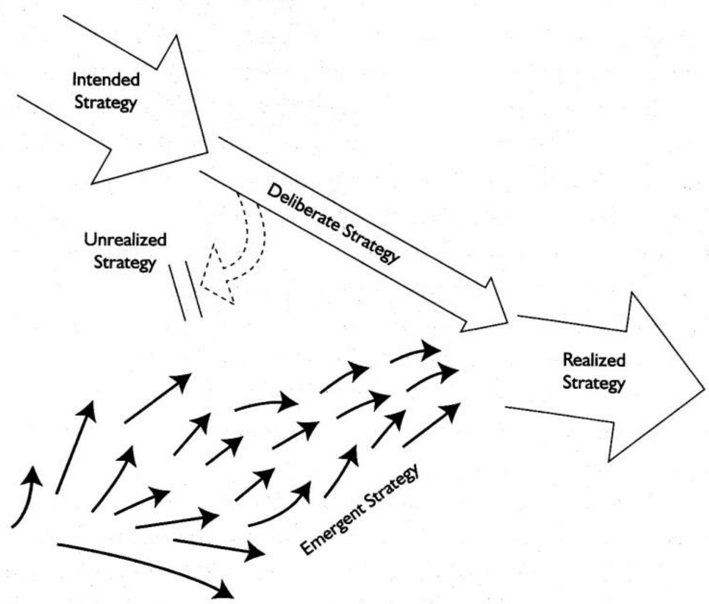
Figure 7: Mintzberg's five Ps for strategy



Source: Own elaboration

It is particularly worth noticing the distinction between *deliberate strategies* (strategy as plan) and *emergent strategies* (strategy as pattern) (Mintzberg, 1978). Deliberate strategies are those in which formulation precedes implementation to pursue a certain pattern of action, whereas emergent strategies are those in which formulation and implementation become a fluid process that results in a realized pattern of action. Fully deliberate and fully emergent strategies may be considered as *"two ends of a continuum in which real-word strategies lie"* (Mintzberg and Waters, 1985). Figure 8 represents visually how deliberate and emergent strategies integrate to result in realized strategies.

Figure 8: Visual representation of the relationship between deliberate and emergent strategies

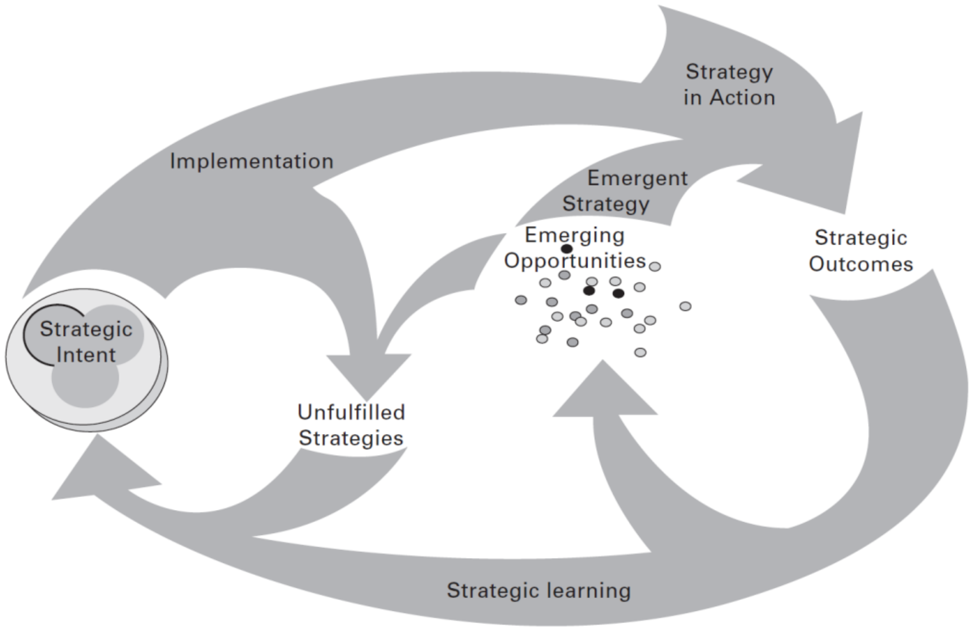


Source: (Mintzberg et al., 1998)

For some, the essence of strategic management is in the formulation and subsequent implementation of deliberate strategies. As such, they tend to put the emphasis on how *planning* a strategy may help an organization identify and pursue a certain position in the market so as to achieve and sustain competitive advantage (Porter, 1998). However, others defend that organizations cannot really aim to identify analytically the position to be pursued, particularly in highly complex environments, and therefore should regard strategic formation as a process of *crafting*, rather than planning (Mintzberg, 1987b). In this view, strategy is not so much a matter of pursuing an intended position, but a matter of realizing the full potential of the organization as it emerges from its capabilities. Therefore, according to this view, the challenge is not so much 'finding' or 'choosing' generic strategic positions (Porter, 1996), but to "*'induce' and 'invent' novel strategic perspectives*" (Mintzberg et al., 1998).

In most real-world cases, as we already mentioned, strategy seems to be a combination of both perspectives, blended in a dynamic process that includes strategic intent and implementation, strategy emerging from opportunities and action, and also strategic learning -see Figure 9 for a visual representation.

Figure 9: Strategy as a process



Source: (Moncrieff, 1999)

1.2. Strategy in the context of energy innovation policy

Could the concept of 'strategy' be useful for public policy-making? If we go to the literature, we find some interesting early attempts to apply insights on strategy from management and organizational studies to public policy (e.g. Jørgensen and Mintzberg, 1987). In the context of energy innovation policy, we also see how the term strategy is frequently used in policy discourses -e.g. the European Commission published a communication to set out an "energy technology and innovation strategy to 2020 and beyond" (European Commission, 2013). However, as others exploring the possibilities of strategic policy-making for energy innovation (Quitzow, 2015b), we conclude that formalized concepts of strategy have been largely missing in policy studies.

Nevertheless, we still think energy innovation policy needs to be approached with some strategic perspective, particularly in view of the broad long-term nature of the sustainability challenges it needs to deal with. Mintzberg et al. (1998) note some potential advantages often associated with strategy, which can also turn into disadvantages in some contexts -see Box 3 for the four they point out. If we read them with the 'energy innovation policy in response to sustainability challenges' lens, we discover that three out of the four they mention become essential: setting direction, focusing effort and providing consistency.

Box 3: Double-edged advantages/disadvantages associated with strategy

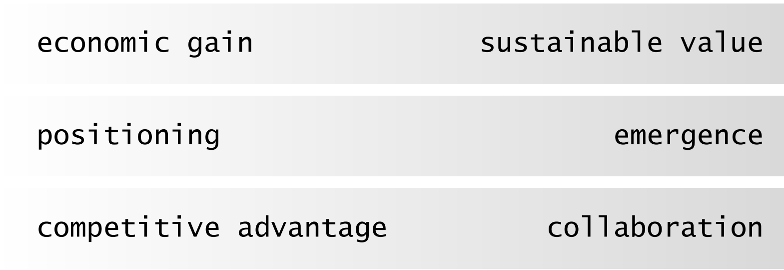
1. 'strategy sets direction'
2. 'strategy focuses effort'
3. 'strategy defines the organization'
4. 'strategy provides consistency'

Source: (Mintzberg et al., 1998)

An strategic perspective also appears crucial when we put the 'energy innovation policy in response to countries' quest for prosperity' lens, particularly as countries' welfare becomes affected by the forces of globalization (Borrás et al., 2009; Edquist and Hommen, 2008).

In any case, we suggest that the strategic perspective for energy innovation policy-making needs to rely on an updated interpretation of the concept, and of course be ready to serve public interests. We appreciate an evolution of the interpretation of strategic approaches in the literature: the purpose of the strategy broadens from economic gains to sustainable value; the focus of strategy formation shifts from positioning to emergence; and the emphasis on competitive advantage leaves room for synergistic collaborative relationships. We synthesize this proposition in Figure 10.

Figure 10: Evolving paradigm for strategic approaches?



Source: Own elaboration

The debates undergone in the strategic management literature can also have implications for our interpretation of strategic energy innovation policy. The debate around deliberate vs emergent strategies provides a good example. Understanding the strategic purpose as a position and the strategic process as planning would translate into energy innovation policy investing only in capabilities that contribute to achieve the planned position. Instead, an understanding of strategy as an emergent pattern of action drawing from capabilities that cannot really be anticipated would translate into energy innovation policy aiming to develop a broad range of capabilities. This indeed reflects the same tension between selectivity and diversity present in policy debates (Chaminade and Edquist, 2010 on selectivity; Leach et al., 2012 on diversity). Again, what seems most reasonable is to see these positions as ends in a continuum of possibilities in which adequate balances need to be found.

In an attempt to clarify our use of 'strategy' in what follows in this thesis, we provide here our own interpretation of the term. We define strategy in the context of innovation policy as the dynamic choice of outcomes to be pursued, whether intended or not, taking into account both internal capabilities and the influence of the external environment, and resulting in a certain trajectory towards the future. Thus, following this interpretation, we suggest that strategic innovation policy requires the consideration/observation of at least three key elements:

- outcomes
- internal capabilities
- external relationships

We will come back to these three elements in our evaluation of previous literature to identify the research gap this thesis will aim to cover.

1.3. Strategy for what?

What should be technological innovation for? What would we like to pursue by being more 'strategic'? It is the first, deep question that we need to address if we are to find ways in which we can approach energy innovation policy more strategically. Although most studies on innovation do not tackle the question directly, there is usually an underlying assumption on them. In general terms, the interpretation of the purpose of technological innovation has broadened up from economic growth, to socioeconomic progress, to sustainable development.

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) but 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 (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[14], there is an increasing concern to make innovation work to enable more sustainable futures – the 'innovation is good only if *it is good*' assumption -see Figure 11 for an illustration of the shift in the underlying assumption about the contribution of innovation to prosperity.

[14] see e.g. (Rockström et al., 2009) on planetary boundaries. Challenges are not only environmental, as reflected in the 17 Sustainable Development Goals recently approved (United Nations, 2015b).

Figure 11: Schematic representation of the shift in the underlying assumption about the contribution of innovation to prosperity

innovation is good

~~because it is good~~

if *it is good*

From emphasizing only the positive outcomes to emphasizing its double-edged potential to contribute to sustainability

Source: Own elaboration

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 consider strategic approaches in a way consistent with sustainability goals. We should aim for strategies that can be related to the generation of welfare from an ample, dynamic, long-term perspective: ample because it should go beyond economic benefits to incorporate the social and environmental; dynamic, because it needs to recognize that innovation is the result of multiple interrelated activities that co-evolve immersed in complex dynamics; long-term because it has to recognize that innovation is cumulative and path-dependent, which means we need to care not only about observed outcomes now, but also about building capabilities for future developments and about the direction of innovation.

1.4. On the implications of globalization

There is wide recognition that processes of technological innovation are becoming increasingly global (Archibugi and Iammarino, 2002; Borrás et al., 2009), not less so in the context of clean energy technologies (Gallagher, 2014; (Quitzow, 2015a).

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 of trade, production and knowledge networks[15] involve a reconfiguration of innovation dynamics at a global scale (Crevoisier and Jeannerat, 2009; Henderson et al., 2002; Lorentzen, 2008; Narula and Dunning, 2000).

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 (TT) 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).

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

[15] Even when knowledge and capabilities are 'sticky' to some extent, globalization is affecting the way they get built and diffused: 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.

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 relates 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.

2. State of the art

In this section we will review the main contributions of different strands of the literature that currently shape our understanding of innovation processes and the frameworks they have suggested for innovation policy analysis.

2.1. Three perspectives shaping our understanding of innovation

Innovation processes have been explored in the literature from many different angles and at multiple levels: from the micro perspective (e.g. conditions for creativity and entrepreneurship), meso (e.g. innovation in organizations and networks), or macro (e.g. innovation policy for economic development). At the policy level, we have identified three strands of the literature that are particularly relevant: neoclassical economics, innovation systems and sustainability transitions.

2.1.1. Neoclassical innovation economics

At the macro level, neoclassical economics have studied how innovation contributes to economic growth. Basic models of economic growth based on capital accumulation could not sustain long-term growth due to diminishing returns to capital. The economist Robert Solow revolutionized the field by showing how a large share of economic growth could be attributed not to the accumulation of capital but to technological improvements that increased productivity (Solow, 1956). Building on Solow's work, later economists were able to incorporate technological progress endogenously into economic growth models, in what came to be known as endogenous growth theory or new growth theory (Romer, 1986; Aghion and Howitt, 1998). In these models, investments in innovation or human capital present no diminishing returns and therefore allow for long-term, sustained economic growth.

At the meso level, in the fields of innovation and energy economics there has been a focus on assessing quantifiable input-output relationships, and on how resources can be most efficiently allocated. Table 5 provides a categorization of studies providing some quantitative evidence on the effects of energy innovation, according to their time horizon (retrospective or prospective), methodology (econometric analysis or simulation models), and the type of indicator they use (outputs or outcomes: outputs refer to those results of innovation efforts that do not constitute socioeconomic impacts, whereas outcomes refer to socioeconomic impacts).

Table 5: Categorization of studies providing quantitative evidence on the effects of energy innovation

Time horizon	Retrospective	Prospective
Methodology	Econometric analysis	Simulation models
Indicators	Outputs: - patents - publications - cost reductions - installed units…	Outcomes: - savings in energy systems - productivity - employment - emissions reduction…

Retrospective studies have generally used econometric techniques to prove certain correlation between inputs and outputs/outcomes in the past (e.g. Horbach and Rennings, 2012), whereas prospective studies have generally used simulation models to assess the magnitude of some expected effects in the future (e.g. Anadón et al., 2011).

Patent counts have been extensively used as an indicator of innovation output, not because they are the most significant indicator, but due to the availability of data (Moser, 2013). Patent analysis may be useful to understand some aspects of technology development (CRIC, 1998), deployment (Popp et al., 2011) or transfer (Dechezleprêtre et al., 2009a; Hall and Helmers, 2010). It may also be useful to evaluate the impact of certain factors –such as energy prices (Popp, 2001)- or certain policies (Johnstone et al., 2010; Bäckström, 2012; Dechezleprêtre and Glachant, 2012), or to identify trends in certain technologies or countries (IRENA, 2013). However, the information patents can provide is very limited for at least three reasons: (1) many innovations are not patented, (2) not all the patents are actually applied in commercialized technologies, and (3) patent counts only reflect quantity but not quality (the value of patents can be greatly divergent). Thus, patents represent only intermediate outputs of innovation efforts, but do not reveal the resulting socioeconomic effects.

Technology cost reduction is another important indicator of an intermediate result of innovation (which may then be used to assess socioeconomic outcomes such as savings in energy systems). Here again, the distinction between retrospective studies and prospective studies is relevant. Some studies have analyzed the evolution in the cost of certain technologies in relation to some innovation inputs, mainly installed capacity and R&D investment. These relationships are often expressed as learning rates (Jamasb and Kohler, 2007; Wiesenthal et al., 2012a): "learning-by-doing" rates provide the ratio between accumulated installed capacity and cost reduction (McDonald and Schrattenholzer, 2001; Sagar and van der Zwaan, 2006; Berglund and Söderholm, 2006), whereas "learning-by-searching" rates provide the ratio between R&D investment and cost reduction (Klaassen et al., 2005; Kouvaritakis et al., 2000). Some other studies have evaluated what the future cost of technologies will be depending on different scenarios of R&D investment into the future. This is often done through expert elicitation (Anadon et al., 2013; Bosetti et al., 2012; Baker et al., 2009; Chan et al., 2010; Anadon et al., 2012 Catenacci et al., 2012; Baker et al., 2010).

There are of course some studies that have gone beyond innovation outputs to try to assess innovation outcomes. Some of them have focused on the returns of public expenditure on R&D activities. For the US, (NRC, 2001) has evaluated the realized returns[16] of energy efficiency R&D programs funded by US DOE, and (Anadon et al., 2011) have evaluated expected savings in the US energy system for different R&D scenarios into the future. Similarly to the latter but in the European context, (Wiesenthal et al., 2010) have evaluated savings for the European energy system of R&D investments consistent with the EU SET Plan, and (Economics for Energy, 2012) has estimated the potential savings in the Spanish energy system.

Another group of studies has looked at different effects of innovation activities at the firm level. For instance, (Harrison et al., 2008) assess the impact of process and product innovations on employment growth, (Griffith et al., 2006) evaluates the increase in productivity achieved through absorptive capacity enabled by R&D activity, and (Peters et al., 2013) use a model to estimate productivity effects and future profits thanks to R&D. In a similar way, FECYT (2012) does an interesting exercise for Spain, in which the effects of innovation on the firms' productivity, exports and sales are assessed using an empirical model.

Some other studies have tried to assess macroeconomic effects of innovation. (Laitner et al., 1998) analyze the effect on employment and other macroeconomic benefits of innovation-led climate strategy for the US, (WWF, 2011) assesses the value added by the

[16] They consider economic, environmental and security benefits, both quantitative and qualitative, and include not only realized benefits but also "options benefits" (technology that is technically proved but is not likely to have favorable economic and policy conditions) and "knowledge benefits" (advances in knowledge that have not led to a fully developed technology).

production of clean technologies in several countries, and (IRENA, 2011) estimates job creation in the renewable industry worldwide.

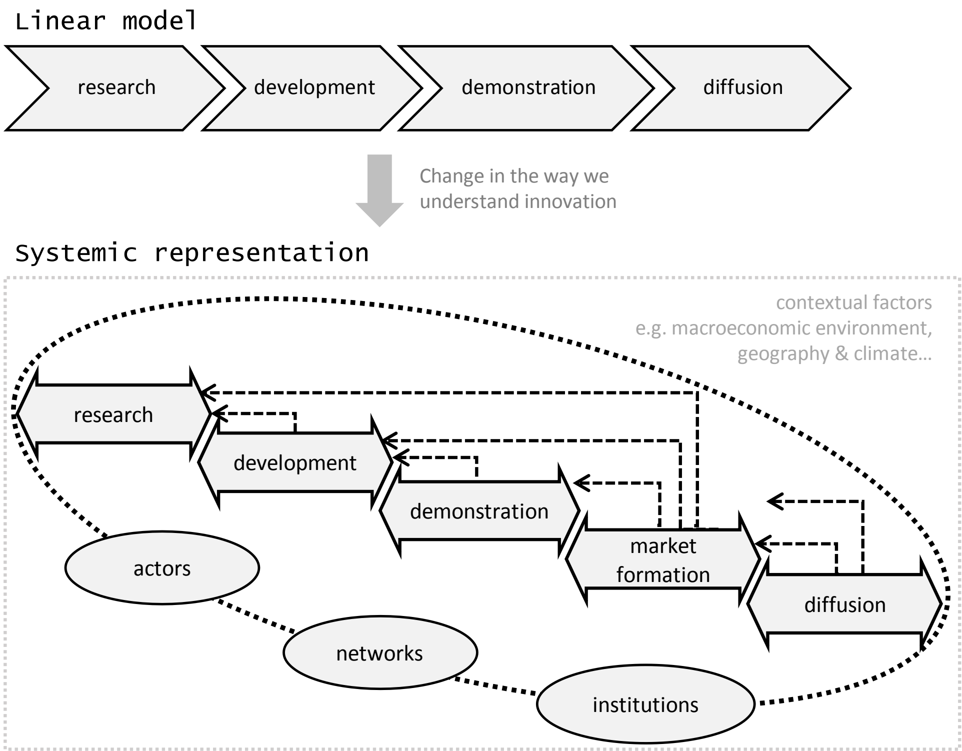
Finally, some studies have tried to assess the environmental effects of energy innovation, particularly on climate mitigation. A good example is (Bosetti et al., 2011a), which evaluates the environmental and mitigation cost implications of climate-related R&D using an integrated assessment model.

All these studies, as relevant as they are, necessarily look only into one part of the picture (one type of output/outcome, one stage of the innovation process, one type of technology, or one country). However, if we want to enable a strategic perspective for energy innovation policy that allows policy-makers to better decide where to focus their efforts, we would need to bring those studies together, complement and structure them if necessary, to provide a comprehensive overview of the outcomes that can be achieved.

2.1.2. Innovation systems

Our understanding of how innovation processes unfold has greatly been enriched by the innovation system (IS) literature. In a time when innovation processes were understood as highly linear and decoupled from societal structures and dynamics, innovation systems pioneers remarked the importance of interactions among the actors involved in the innovation process -people, enterprises, institutions (Dosi et al., 1988; Freeman, 1995; (Lundvall et al., 2002). Figure 12 shows how we moved from a linear understanding of innovation processes -from research to development to demonstration to diffusion- to a more systemic, chain-linked model with multiple feedback loops in the innovation process (Kline and Rosenberg, 1986).

Figure 12: How our understanding of innovation processes evolved from linear models to systemic representations



Source: Adapted from (Grubler et al., 2012a)

From there, a wealth of research has been developed to better understand innovation systems as defined by different system boundaries -national, regional, sectoral or technological- resulting in different strands of literature. Table 6 gathers these four strands of the innovation systems literature and provides their classical references.

Table 6: Four main strands in the innovation systems literature, with some classical references

Strands in the IS literature		Classical references
National Innovation System	-NIS	(Edquist, 1997; Lundvall, 1992; Nelson, 1993)
Regional Innovation System	-RIS	(Cooke et al., 1997; Maskell and Malmberg, 1999)
Sectoral Innovation System	-SIS	(Malerba, 2002; Malerba and Breschi, 1997)
Technological Innovation System	-TIS	(Carlsson and Stankiewicz, 1991)

The innovation systems literature is built on theoretical grounds different to those of the neoclassical perspective described previously. It draws instead from evolutionary theory. From an evolutionary perspective, the processes of technological and economic change can be somehow comparable to the Darwinist processes of natural selection in biology, in which mechanisms of selection, variation and self-replication can be identified

(Nelson and Winter, 1982). The Schumpeterian view of innovation as a process of 'creative destruction' (Schumpeter, 1942) can be considered a predecessor of evolutionary views.

From an evolutionary perspective, there is no ideal point of equilibrium, which means we cannot aim for optimizing strategies, but rather for satisficing strategies (Simon, 1956). Moreover, the focus shifts from resource allocation to the facilitation of systemic conditions, particularly those that favor interactions (Chaminade and Edquist, 2010). Even the language of the approaches changes, with neoclassical perspectives being keener to use mechanistic terms (e.g. the push and pull forces) whereas evolutionary perspectives prefer terms inspired in the biological and ecological world (e.g. ecosystem, niches, etc.).

2.1.3. Sustainability transitions

Technological innovation is not neutral: it transforms our socioeconomic systems in certain directions. This pretty obvious observation was however not present in the previous perspectives just described, which have put the emphasis on innovation as a source of increased productivity and economic growth (neoclassical economics), and on how its processes unfold (innovation systems), but not so much on how it impacts our societies and environment. Now that we have reached a point in which we realize our socioeconomic systems have become unsustainable in many ways (e.g. Rockström et al., 2009; Raworth, 2012), many argue that it becomes crucial to orient innovation towards sustainable solutions.

Achieving sustainable modes of production and consumption calls for profound transformations of our current socio-technical systems, in what can be called 'sustainability transitions'. Sustainability transitions can be defined as long-term, multi-dimensional shifts from established socio-technical systems to more sustainable modes of production and consumption (Markard et al., 2012). Socio-technical transitions involve much more than new technologies: they require changes in markets, user practices, policy and cultural discourses, and governing institutions (Geels et al., 2008). They usually involve a sense of direction, being guidance and governance a particularity of sustainability transitions (Smith et al., 2005).

As the innovation systems perspective, the sustainability transitions perspective is grounded on an evolutionary understanding of innovation processes, but one that puts the focus on the long-range dynamics of system evolution rather than on the internal workings of the system. Indeed, we could say that the focus in this strand of the literature is not any more on building 'innovation systems' but on spurring 'system innovation' (Elzen et al., 2004; Geels, 2005; OECD, 2015).

Table 7 summarizes the main shifts from the 'innovation systems' perspective to the 'system innovation' perspective, according to Geels (2013).

Table 7: Innovation system approach vs. system innovation approach

Innovation system <	> System innovation
Upstream focus on knowledge	Focus on production and consumption/use
Focus on improving the functioning of existing systems	Focus on shift to new socio-technical systems
Focus on speed (knowledge flows) and outputs (patents, products)	Additional focus on direction of innovation (problem and goal-oriented)
Focus on generic conditions and system elements that favor innovation in an abstract sense (mainly knowledge)	Focus on concrete technologies and sectors (consumers, firms, industries, special interests, public)
Limited attention for agency	Acknowledgement of different interests, strategy, conflict, power struggle, disagreement
Methodologically advanced (indicators, measurement, benchmarking)	Methodologically open (as it is a new, emergent topic)

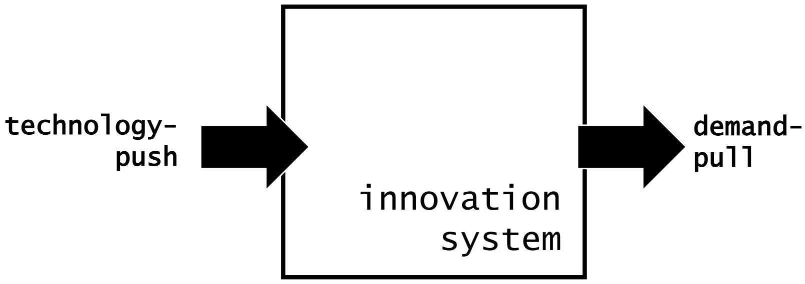
Source: Adapted from (Geels, 2013)

2.2. Frameworks used for innovation policy-making

2.2.1. Technology-push / Market-pull

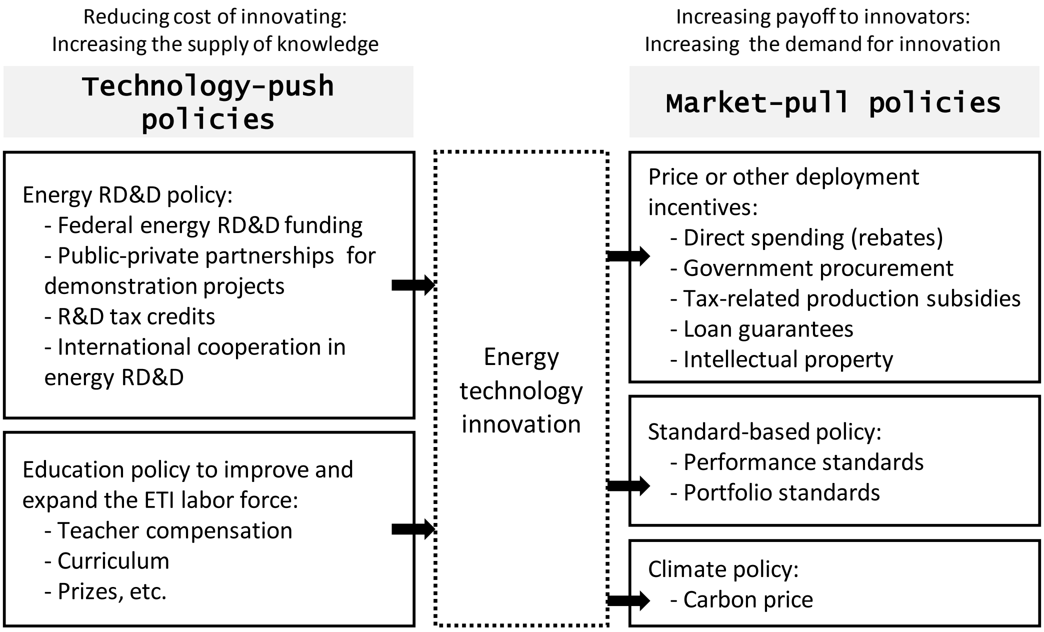
From the neoclassical perspective, the aim of innovation policy-making should be bringing the system closer to the social optimum by correcting market failures. This can be done namely in two ways: by increasing the supply of knowledge (technology-push) or by increasing the demand for innovation (demand-pull) (Nemet, 2009). Under this framing, innovation processes are treated as black-box affected by technology-push and demand-pull forces -see Figure 13 for an illustration, and Figure 14 for examples of policy options considered under each of these categories.

Figure 13: Technology-push and market-pull forces affecting the innovation system as a 'black box'



Source: Own elaboration

Figure 14: Examples of technology-push and market-pull policies



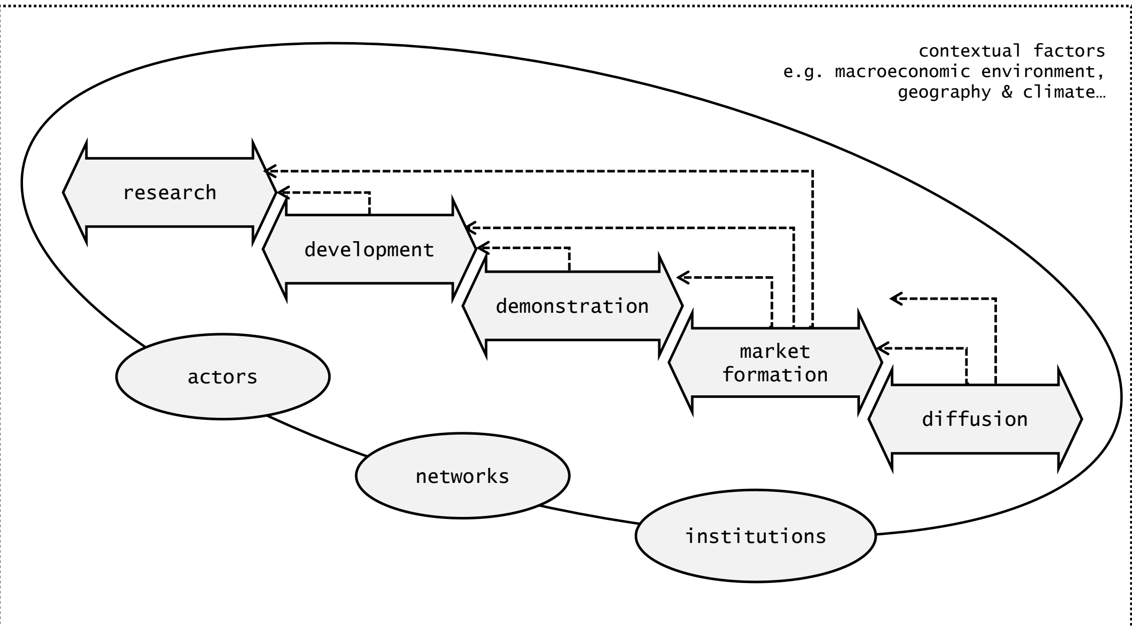
Source: Adapted from (Anadon and Holdren, 2009), based on (Mowery and Rosenberg, 1979)

2.2.2. Technology innovation systems: ETIS and functional approach

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., 2012b). 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 15 provides a representation of ETIS.

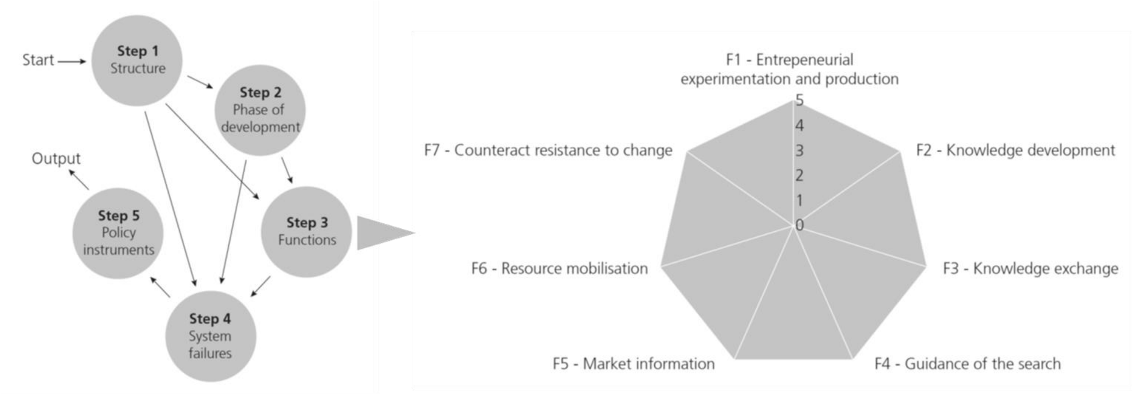
Figure 15: Energy technology innovation system



Source: Adaptation 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 16 illustrates the policy analysis proposed by the functional approach to TIS, including the analysis of seven functions: entrepreneurial experimentation and production (F1), knowledge development (F2), knowledge exchange (F3), guidance of search (F4), market information (F4), resource mobilization (F6) and counteract resistance to change (F7) (Hekkert et al., 2011).

Figure 16: Schematic of the policy analysis proposed by the functional approach to TIS



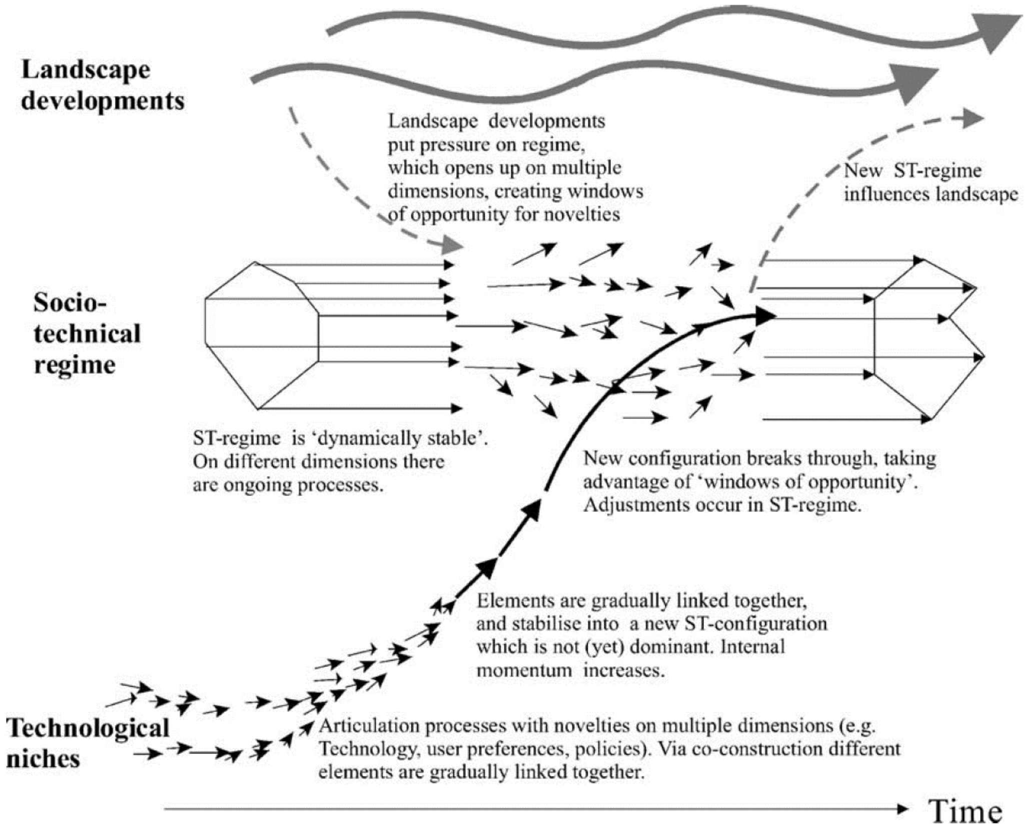
Source: (Hekkert et al., 2011)

2.2.3. The multi-level perspective and transitions management

In the field of sustainability transitions, we find the Multi-Level Perspective (MLP) proposed by Geels (2002) as an analytical framework with much traction recently. MLP explains technological transitions through the dynamic interplay of three levels: niche (micro), regime (meso) and landscape (macro). The regime corresponds to the dominant technologies and practices operating in a stablished, stable socio-technical system. The niche corresponds to the technologies and practices emerging from experimentation with the potential to generate disruptive innovation. The landscape constitutes the external structure or context for interactions, including social values, prices, political situation, etc.

Technological transitions observed through the lens of the multi-level perspective can be explained as a process in which a stablished socio-technical system is destabilized thanks to the confluence of pressure from landscape developments -which creates windows of opportunity- and the increase in momentum of radical innovations emerging from niche (Geels, 2004). Thus, radical innovations may break through and transform the socio-technical regime into new configurations. Figure 17 provides a graphical representation of this interpretation.

Figure 17: Dynamic multi-level perspective of technological transitions



Source: (Geels, 2004)

Policy approaches using evolutionary perspectives in the context of sustainability transitions include transition management and strategic niche management (Nill and Kemp, 2009):

- The strategic niche management approach suggests that creating and nurturing technological niches may facilitate sustainability transitions. Niches are defined as "protected spaces that allow experimentation with the co-evolution of technology, user practices, and regulatory structures" (Schot and Geels, 2008).
- Transitions management proposes participatory processes of visioning, learning and experimenting –"the objectives and final visions are determined socially, not just by expert scientific knowledge" (Rotmans et al., 2001). Box 4 summarizes some key characteristics of the transitions management approach.

Box 4: Summary of characteristics of transitions management

- Long-term thinking (at least 25 years) as a framework for shaping short-term policy
- Thinking in terms of more than one domain (multi-domain) and different actors (multi-actor) at different scale levels (multi-level)
- A focus on learning and a special learning philosophy (learning-by-doing and doing by- learning)
- Trying to bring about system innovation alongside system improvement
- Keeping a large number of options open (wide playing field).

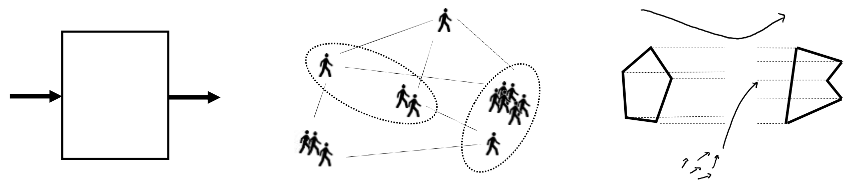
Source: (Rotmans et al., 2001)

2.3. Comparison of perspectives

The perspectives and frameworks we just reviewed look at innovation from different angles, and are able to reveal different aspects of innovation processes and suggest different policy approaches to improve them. In

Table 8 we offer a comparison of the three perspectives on key aspects, such as the underlying assumption they build on, the type of relationships they put their focus on, and the aim of the policy approaches resulting from them.

Table 8: Comparison of three reviewed perspectives



	innovation economics	innovation systems	sust.transitions
perspective	neo-classical	evolutionary	
underlying assumption	equilibrium	non-equilibrium	
analyzed relationships	input-output	actors-networks-institutions	niche-regime-landscape
policy goal	allocating resources, correcting market failures	nurturing ecosystems favoring interactions promoting learning	creating visions, redefining trajectories, supporting niches
language	mechanistic e.g. push & pull forces	inspired in biology and ecology e.g. ecosystem, niche…	
interpretation of strategy	plan/position -intended strategy	pattern -realized strategy	

Source: Own elaboration

These three perspectives are often presented separately in the literature, and even with some degree of confrontation between the neoclassical approaches and the evolutionary approaches. However, could they just be offering different perspectives of a very complex reality that needs to be understood from as many angles as possible? In Box 5 we illustrate how, in our view, all the perspectives seem to be relevant for designing innovation policy using the 'innovation as a sailing journey' metaphor.

Box 5: How all perspectives matter using the 'innovation as a sailing journey' metaphor.

We use italics to emphasize some concepts that are key for the particular perspective being described

What is needed for a successful journey?

- Allocating resources (neoclassical economics)

We need resources for the ship, both in terms of materials for the vessel (wood for the masts, cloth for the sails…) and in terms of food and fresh water for the sailors. If we could *allocate* these resources *efficiently* according to the needs and potential for improving navigation, perhaps we could reach an *optimal* situation for everyone, as we would be maximizing our opportunities to succeed in the journey.

- Knowledge, interactions, institutions (innovation systems)

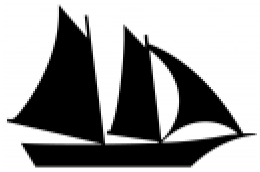
Another important factor for a successful trip will be the sailing *knowledge* of the sailors, as a result of their education and their accumulated experience. Their willingness to assume the risk of embarking in such an uncertain journey, their *ability* to adapt and come up with solutions onboard, and their *attitudes* to face tough moments onboard will also be important.

Some sailors will join the ship full of expertise, some others will enter as cabin kids and will need to learn along the way. Sharing information and encouraging *learning* will therefore become crucial to keep building sailors' *capabilities* all along the journey. Moreover, analyzing potential improvements and trying out novel navigation techniques (*R&D*) will be an opportunity to improve their capabilities and hopefully (but not surely) improve their chances for succeeding in the journey.

Interactions among sailors are also crucial. If sailors are able to communicate and cooperate we could be expecting the activities onboard to be carried out much more *effectively.* Formal rules may play a role to establish limits or provide incentives, as do shared values or informal social norms among the sailors (*institutions*).

- Changing course (sustainability transitions)

The ship can go adrift and still move somewhere. This may be fine if all directions provide equal opportunities for success. But what if we knew that we will very likely reach a terrible storm if we just let the ship move the direction it has taken? Then it becomes important to redirect the course… We may not know exactly where we want to go, but we surely know we want to avoid the storm.



3. The research gap

Let's come back now to our research question: *How could countries undertake energy innovation policy more strategically? - in such a way that innovation efforts can be directed effectively to advance towards more sustainable energy systems and realize welfare-improving benefits*. Now, are the perspectives and frameworks we have reviewed ready to respond to this question?

We evaluate to what extent these perspectives provide suitable basis for the considerations of the three elements we identified as key for strategic thinking in the context of energy innovation policy (from Section 1): outcomes, internal capabilities and external relationships. The conclusions from this analysis are summarized in Table 9.

Table 9: Evaluation of the extent to which current perspectives on innovation facilitate the consideration of relevant-for-strategy elements

	innovation economics	innovation systems	sustainability transitions
outcomes	◐ partial or macro	◐ diffusion of technology	◐ impact on socio-technical regime
internal capabilities	◐ production factors	● structure and dynamics	◐ niche developments
external relationships	◐ spillovers, technology transfer	◐ supranational TIS or SIS	◐ landscape developments

Does the perspective provide suitable basis to consider this aspect?

○ Not really ◐ Only to some extent ● Yes, it is particularly strong in this

Source: Own elaboration

If we focus on innovation systems, as the approach that has most explored the intricacies of innovation processes, we see how they are particularly strong in taking into account internal capabilities through their thorough analysis of structure and dynamics.

However, we argue the way they are currently conceptualized is not fully suitable to enable the kind of strategic thinking that we proposed for two main reasons.

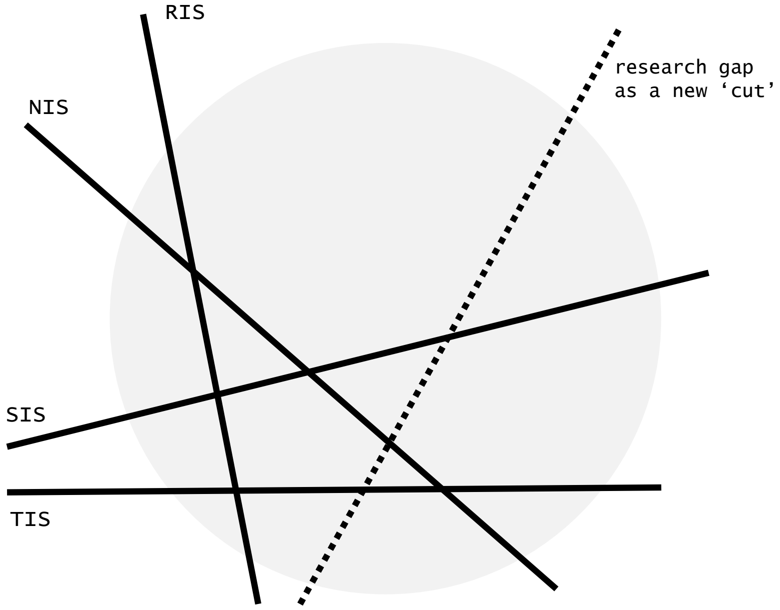
First, because the explicit consideration of differentiated outcomes has not been a relevant concern in national/regional/sectoral innovation systems, which have typically assumed that innovation is a desirable thing to be pursued, as a source of competitiveness and socioeconomic benefits. In the case of technological innovation systems (TIS), 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), which we argue does not provide a useful approximation for policy makers: 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.

Second, regarding the consideration of international relationships, national/regional/sectoral innovation systems have focused on the interactions within their boundaries (defined by national, regional and sectoral borders), failing to *"address the disruptive challenges posed by globalization on the geography of innovation systems"* (Ernst, 2002 -discussing NIS). TIS have put the development and diffusion of specific emerging technologies at the center of the analysis, and 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, we suggest that innovation policy could benefit from a representation of innovation systems for energy technologies that puts the consideration of both outcomes and global dynamics at its core.

If we think of innovation processes as a very big sphere full of complexity inside, we can interpret the different strands in innovation systems literature as different 'cuts' to the innovation reality, ready to reveal different aspects of its complexity. In this PhD thesis we would like to contribute to the innovation studies literature by providing a new 'cut' of innovation processes, one that is more ready to reveal differentiated outcomes and international dynamics. Figure 18 provides a visual illustration of our interpretation of the research gap as a new cut to the complex innovation reality.

Figure 18: Interpreting the research gap as a new cut to the complex innovation reality



Source: Own elaboration

In providing this new 'cut' we aim to integrate insights from the three perspectives reviewed. Indeed, we believe that we need the three perspectives to be able to incorporate sufficiently economic and market dynamics (where innovation economics is strongest), knowledge and institutional dynamics (where the innovation systems approach is strongest), and transformational dynamics (where the sustainability transitions approach is strongest). We summarize these relative strengths of the different perspectives in Table 10.

Table 10: Evaluation of the relative strengths of different perspectives on innovation

	innovation economics	innovation systems	sustainability transitions
economic & market dynamics	●	◐	○
knowledge & institut. dynamics	○	●	◐
transformational dynamics	○	○	●

Does the perspective provide suitable basis to consider this aspect?

○ Not really ◐ Only to some extent ● Yes, it is particularly strong in this

Source: Own elaboration

To close this chapter, as a synthesis of the literature review undergone, we illustrate in Box 5Box 6 how we have progressively improved our knowledge on innovation processes and how we now need to incorporate the global dimension using the 'innovation as a sailing journey' metaphor.

Box 6: Summarizing the literature review and the research gap with the 'innovation as a sailing journey' metaphor

What do we need to understand better to improve navigation?

Coming back to our sailing ship… For some time we have focused on how to increase its speed. The implicit assumption has often been *the faster, the better*. We studied how to allocate resources or introduce some fixes to the ship to accelerate speed. We also studied how the relationships among the sailors and the procedures and rules they introduced affected it.

At some point we began realizing that perhaps our focus on speed had prevented us to appreciate we were heading towards where we didn't want to be. For many, it was *not anymore just a matter of speed, but also of direction*. So we began studying how to change the course of the ship so we could move towards more desirable horizons -which is far from easy given the immense inertia the ship has and the perceived urgency of doing so.

To make our navigation decisions even more complex, we are only recently realizing that our ship can not really be considered in isolation from other ships in the sea: sailors can jump from one ship to other, resources can be exchanged, navigation tips and techniques can be transferred across ships more easily than ever before… Furthermore, we came to realize that some of the challenges we face can only be solved by coordinating and adding up efforts across ships. However, our understanding of this dimension is still very limited.

Chapter 4_

Methodology

A visual framework to support
an outcome-oriented, global view
of technological innovation

Methodology. A visual framework to support an outcome-oriented, global view of technological innovation

In Chapter 3 we have discussed how a view on innovation systems that puts considerations of outcomes and international dynamics could be useful for innovation policy-making. Responding to this need, we devote Chapter 4 to propose the Outcome-oriented Innovation Framework (OoIF) specifically conceived for that.

In building our framework, we will rely on previous literature on innovation systems, 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. 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 by (Kline and Rosenberg, 1986), or the representation of the multi-level perspective by (Geels, 2002), both offering powerful diagrammatic representations of complex concepts and dynamics.

We turn now to present OoIF, breaking its description around four key aspects: link innovation outcomes-sustainability (Section 1), system definition and building blocks (Section 2), dynamics within the system (Section 3), and dynamics across systems (Section 4). We will conclude the Chapter reflecting on the limitations and applications of the framework (Section 5).

1. Interpreting innovation outcomes

1.1. Through the lens of sustainability

Following the discussion in Section 2.2, we propose that the purpose of technological innovation should be interpreted through the lens 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.

Although there is no single interpretation of what constitutes 'sustainability', and a careful consideration of the concept is beyond the purpose of this thesis, 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. We suggest that 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 CO2 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.

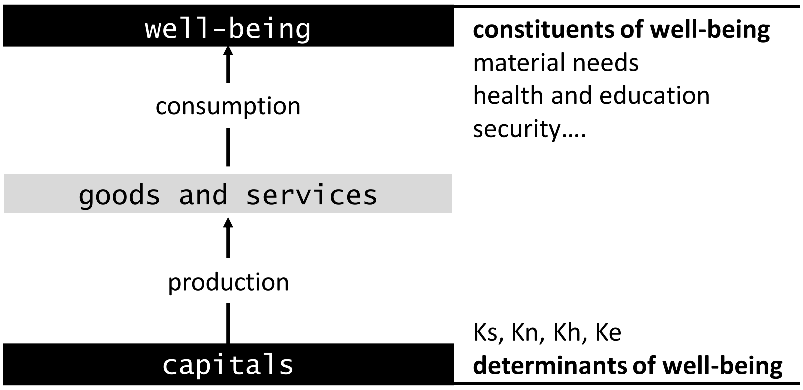
Note that while this conceptualization of the contribution of innovation to sustainability may sound quite theoretical, it has a rather direct application in policy making. On the one hand, raising capitals in our case translates into easily recognizable policy goals, such as fostering economic activity 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). Increasing the inclusiveness of institutions (Ks) may precisely hold the clue to progress in the equity dimension of sustainability.

1.2. Connection to well-being

In any case, it is true that raising capitals per se is not the final purpose of policy, but an intermediate purpose. The ultimate purpose, at least from an anthropocentric point of view, has to do with increasing people's well-being. To understand how capitals connect to people's wellbeing it is useful to interpret them as the stocks from which we are able to derive the goods and services (in a broad sense, not just commercial ones) that allow us to cover our human needs -see Figure 19 for an illustration. The whole discussion about what constitutes human needs is a fascinating one, with some understanding them as a hierarchy (Maslow, 1943) and others as an interrelated, interactive system (Max-Neef, 1992).

Figure 19: Interpretation of the relationship between capitals and well-being

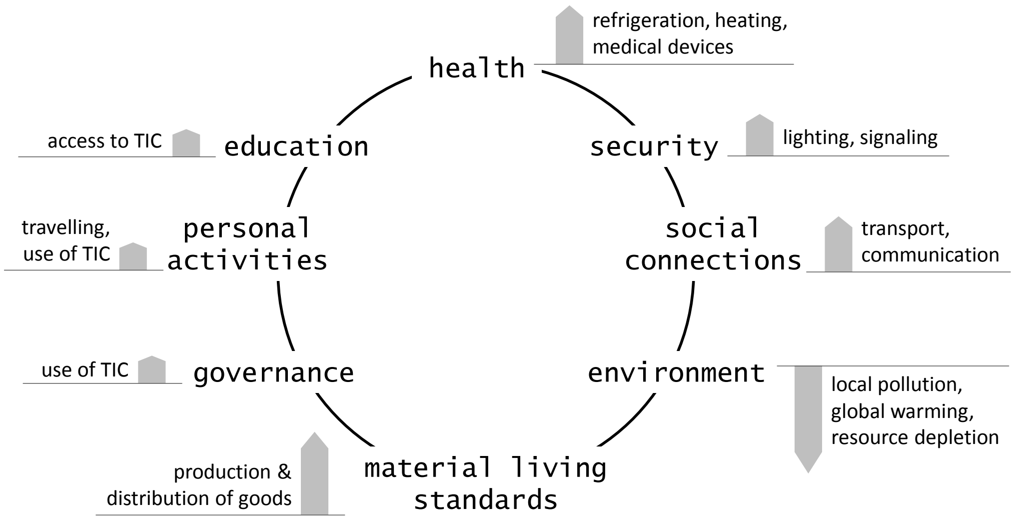


Source: Adapted from (Matson et al., 2016)

If capitals can be considered 'determinants' of well-being (as illustrated in Figure 19), what would be the 'constituents' of well-being? Again, there is no straightforward answer. In 2008, the French governments created a commission with three leading economists -Stiglitz, Sen and Fitoussi- to examine how we could measure the wealth and social progress of a nation beyond GDP. Their study reviewed what fundamental elements contribute to our well-being, and highlighted the following: governance, education, social connections and relationships, personal activities, environment, health, security and the material living standards provided by the triangle income-wealth-consumption (Stiglitz et al., 2009).

If we think how our use of energy impacts these elements -in Figure 20 we have depicted our interpretation- it is easy to realize the profound implications energy has on our well-being. Following this interpretation, energy tends to contribute to our well-being in a variety of ways (although some will depend on the context and can be debatable), but clearly has negative impacts in one of the key constituents of well-being: the environment. Indeed, there is currently a trade-off between all the positive benefits we derive from our use of energy and the very significant environmental impacts we create in doing so.

Figure 20: Interpretation of the impact of energy on the constituents of well-being

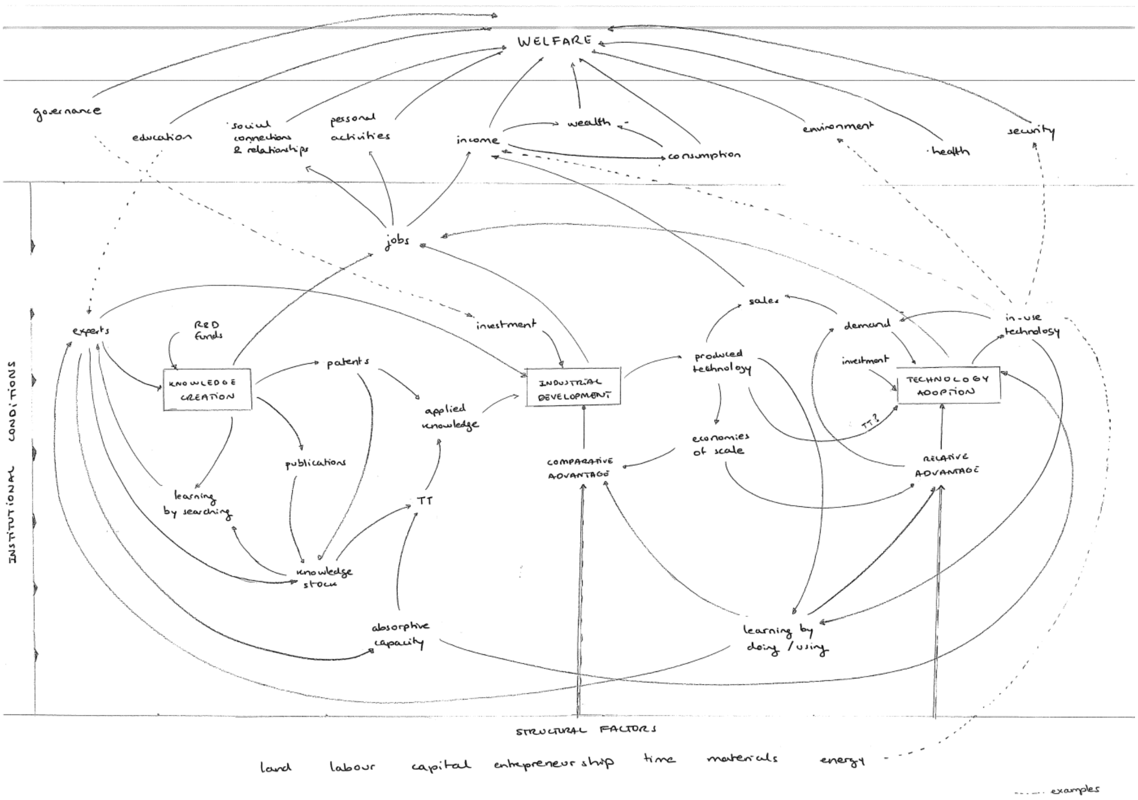


Source: Own elaboration

What would then be the role of energy innovation in contributing to our well-being? On the one hand, it is very connected to what we represented in Figure 20: energy technologies could allow us to widely provide adequate levels of health, material living standards, etc., but we need technologies that dramatically reduce the environmental impact that current technologies have -otherwise it would be unsustainable. On the other hand, we keep mentioning how innovation activities are recognized to contribute to socioeconomic welfare, but the mechanisms in which they do so are still only partially understood.

Could we trace how innovation in energy technologies contributes to the generation of welfare through both processes (the adoption of cleaner technologies and the socioeconomic activities generated thanks to the development of new technologies)? That is exactly what we initially tried to do for this thesis. A representation of the preliminary model we came up with is shown in Figure 21. It was a model inspired in system dynamics, in which we tried to connect inputs, outputs and outcomes of innovation activity. The outcomes we considered were the constituents of well-being already mentioned, that at an aggregated level represent the country's welfare. We depicted some ways in which innovation activities ultimately resulted in increased welfare (providing only examples, not a comprehensive account). For instance, in Figure 21 we see how innovation activities related to knowledge creation, industrial development and technology adoption contribute to the generation of jobs, which in turn becomes a source of income, a means for personal development, and a space for social relationships, and thus results in increased welfare.

Figure 21: Preliminary version of the model to understand how technological innovation contributes to well-being



Source: Own elaboration

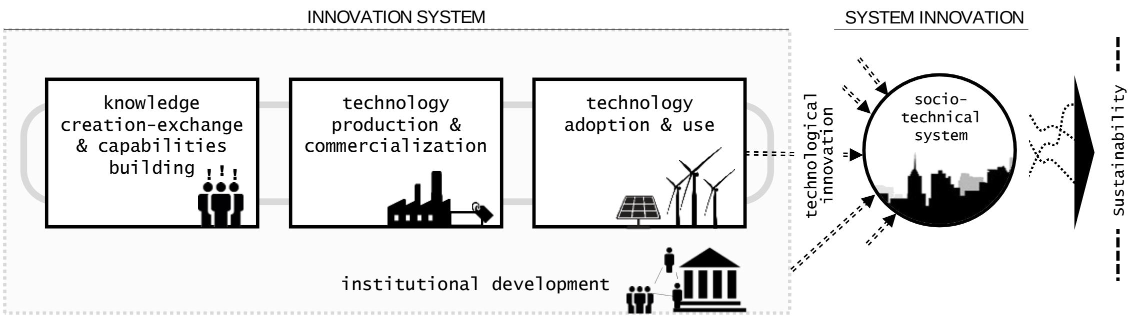
This model provides a perspective of how innovation in energy technologies could contribute to increase countries' wellbeing. However, after a deep dive in innovation studies, we came to the conclusion that this perspective would only allow us to represent input-output relationships (following a neoclassical perspective), but would not be able to reflect adequately knowledge and institutional dynamics (innovation systems perspective) and the relevance of trajectories and transformational dynamics (transitions perspective). In the next section we describe how we came to define the structure of the framework we finally propose, using the more general capitals approach (determinants of wellbeing rather than constituents) to understand the connections between technological innovation and well-being.

2. System definition and building blocks

Building on the previous discussion and on the literature on both innovation systems and sustainability transitions, we turn now to propose the basic structure and building blocks for OoIF, as represented in Figure 22 (OoIF-bb).

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). The *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 (e.g. renewables in our case) get introduced into a *socio-technical system* (represented as a circle) that works towards the fulfilment of a certain societal need (e.g. lighting or transportation). 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). The horizon that seems more suitable nowadays to guide the direction for system innovation is sustainability.

Figure 22: OoIF-bb - Schematic of building blocks in the Outcome-oriented Innovation Framework



Source: Own elaboration

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 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 domain (technology/sector), 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.

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)[17]. They are also easily related to 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

[17] 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).

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).

Box 7: Describing the building blocks of the innovation system in OoIF with the 'innovation as a sailing journey' metaphor

The vessel: three sails, one hull - affected by sailors of course!

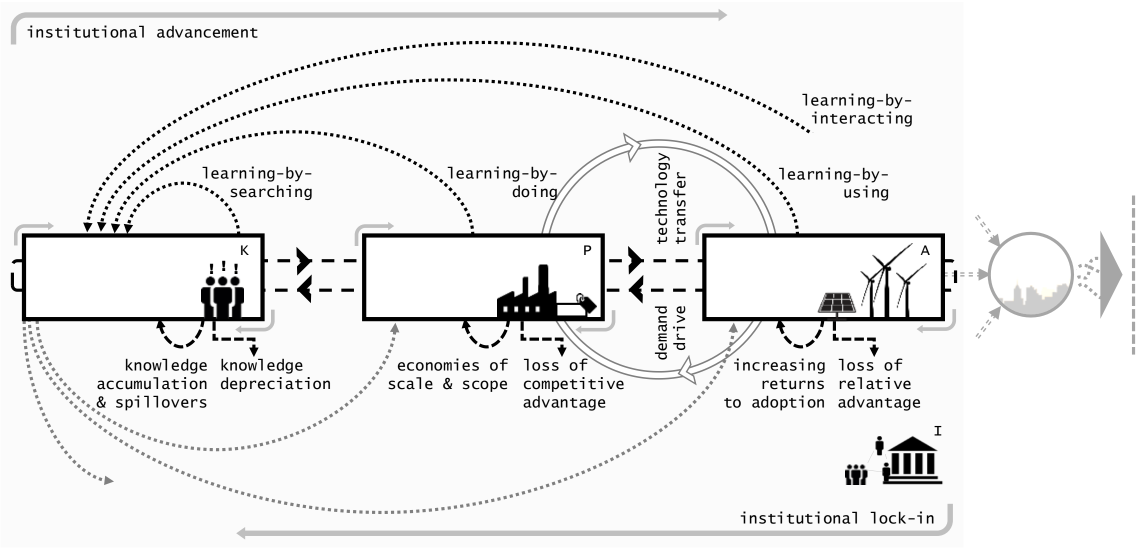
There are many ways in which we may try to describe the vessel of our innovation journey. Here we have focused on four elements: its three sails and the hull. The three sails -which we have named K, P, and A- have distinct but complementary functions. The relative position of the sails conditions how fast the ship can navigate. The hull -which we have named I- is what holds everything together, and includes the helm that can be used to set the direction of the vessel.

Even if we describe the vessel through these elements -hull and sails-, we remain very aware that the vessel is built and operated by sailors. Indeed the vessel itself can be considered the result of the continuous contributions of sailors both in the past and nowadays. The structure and functioning of the hull and sails are constantly being determined by the actions of the sailor -each of them often affecting more than one element in the ship.

3. Dynamics within the innovation system

We will explore now in more detail the left hand-side of Figure 22 to identify dynamics within the innovation system, as represented in Figure 23 (OoIF-dw).

Figure 23: OoIF-dw - Schematic of dynamics within the innovation system



Source: Own elaboration

A quick overview of Figure 23 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 -technology transfer-, 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, following a *circular economy*[18] approach.

[18] https://www.ellenmacarthurfoundation.org/circular-economy

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.

Box 8: Noticing the importance of dynamics within the innovation system with the 'innovation as a sailing journey' metaphor

A ship is much more than the addition of its parts

What makes a ship a ship? Does having three sails and a hull mean we have a ship? Probably not unless these parts are placed and operated in a way that allows them to work as a functioning whole. Thus, elements interlinking the sails and the hull become essential for a ship to work as a ship.

3.1. 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: One, that new knowledge is often generated through interactions -e*xchange*- (Malerba, 2002); and two, 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[19]. 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 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).

3.2. Market dynamics

Market dynamics also play a relevant role in the innovation system. 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.

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 -*technology transfer*- and reacting to identified or created market needs -*demand drive.* 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.

[19] 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.

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[20] (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). 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).

3.3. Institutional dynamics

The institutional context largely affects innovation processes. For instance, interactions among actors allow knowledge to diffuse and be created (in K), the entrepreneurial environment and attitudes affect the probability of new business endeavors (in P), and shared expectations among investors or favorable consumer preferences[21] 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).

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"[22] (Quitzow, 2015a). The role of

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

[21] Dewald and Truffer (2011) discuss how consumer preferences have played a key role in the diffusion of solar PV in Germany, and provided the legitimacy for policy support schemes.

[22] 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

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 also consider how these dynamics may affect activities K-P-A in particular ways.

In Table 11 we summarize the dynamics within the innovation system included in OoIF.

Table 11: Summary of dynamics within the innovation system (OoIF-dw)

↓ Dynamics within	| Activities →
Self-reinforcing	Knowledge accum. & spillovers
	Economies of scale & scope
	Increasing returns to adoption
Weakening	Knowledge depreciation
	Loss of competitive advantage
	Loss of relative advantage
Institutional developments	e.g. new research institutes
	e.g. networks of entrepreneurs
	e.g. consumer preferences
	e.g. introduction of CO_2 price
Institutional lock-in	e.g. lack of communic. channels
	e.g. high business risk
	e.g. incumbent lobbying
	e.g. lack of legitimacy
Learning	Learning-by-searching
	Learning-by-doing
	Learning-by-using
	Learning-by-interacting
Knowledge-market	Horizontal tech. transfer
	Demand-drive

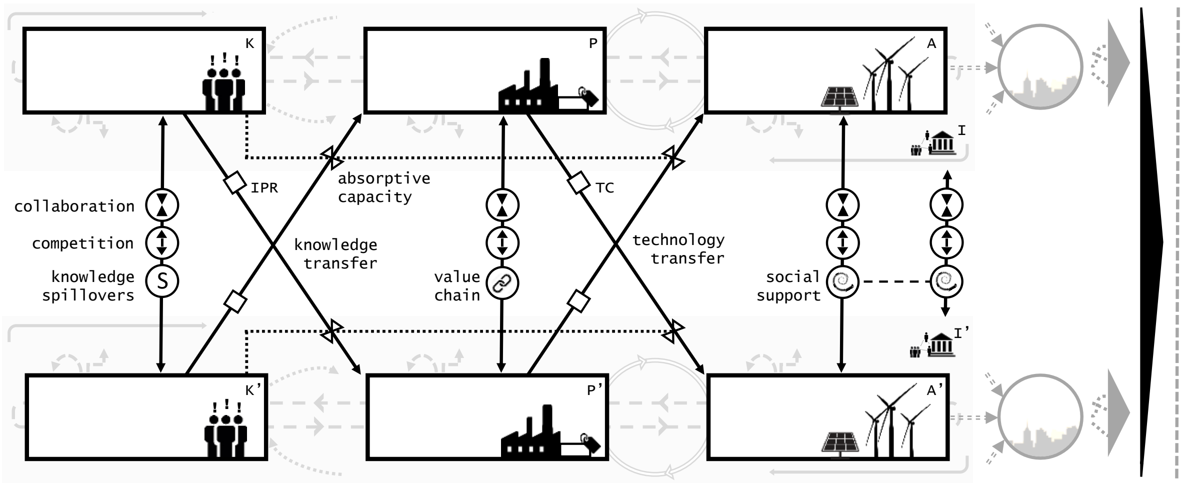
4. Dynamics across innovation systems

If we consider that 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-national dynamics. In Figure 24 (OoIF-dx) we explore these relationships.

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.

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.

Figure 24: OoIF-dx - Schematic of dynamics across innovation systems



Source: Own elaboration

Before further describing these dynamics, note that we have included an additional triangle at the right-hand side of Figure 24 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).

Box 9: Noticing the relevance of cross-national dynamics with the 'innovation as a sailing journey' metaphor

But wait, we are not the only boat in the sea!

Are other boats exploring the same routes? Have they explored them before? Are they likely to take advantage of what we are discovering or could we take advantage of what they have discovered? How our boat interacts with the rest? What type of exchanges are being realized? Could we promote some other exchanges? Is there room for stablishing synergistic relationships across boats?

All these are questions the sailors would probably be asking when they realize they are not alone in the sea, but surrounded by many other boats that largely affect their journey...

4.1. 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).

4.2. 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).

To distinguish TT happening across countries from TT by which knowledge is transformed into marketable products or services within a country, we could talk respectively of *horizontal* and *vertical* technology transfer (Ockwell et al., 2008). OoIF also 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 *horizontal 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 *horizontal 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.

4.3. 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.

4.4. 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.

4.5. 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 intertwined in a process of co-evolution (Nelson, 1994).

In Table 12 we summarize the dynamics across innovation systems included in OoIF.

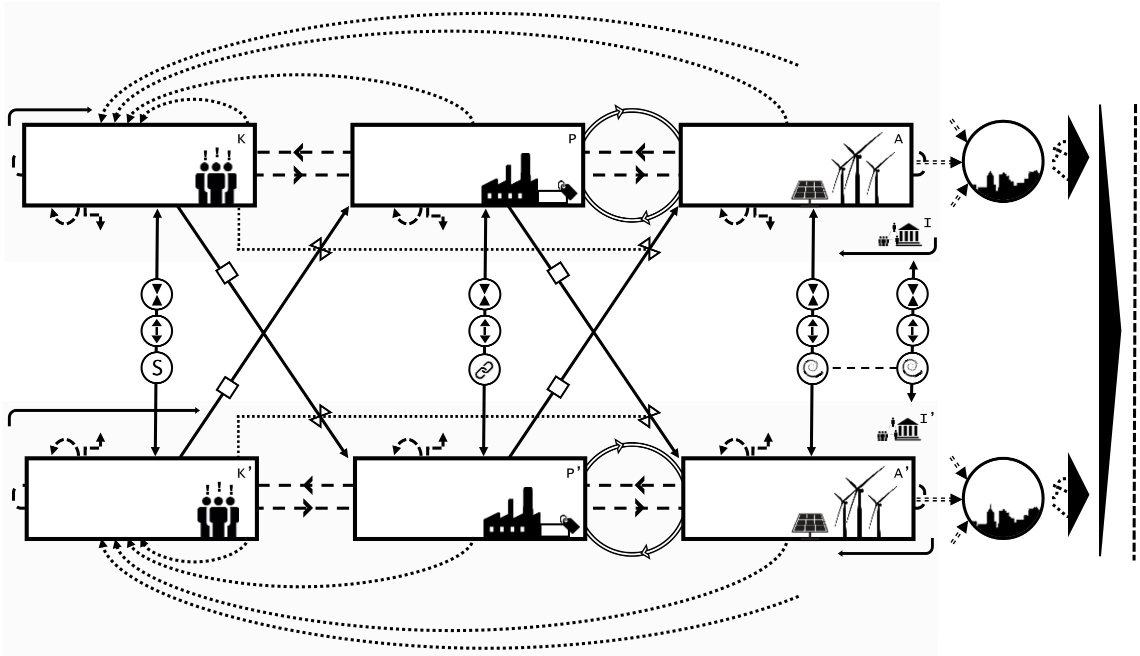
Table 12: Summary of dynamics across innovation systems (OoIF-dx)

↓ Dynamics across	Activities →				
Technology transfer	Vertical knowledge transfer	→	→		
	Vertical technology transfer		→	→	
	> absorptive capacity	⇠	⇠	⇠	
	> intellectual property rights	—□—	—□—		
	> technological characteristics		—□—	—□—	
Competition	e.g. for talent	↕−			
	e.g. in manufacturing cost		↕−		
	e.g. for physical & financial resources			↕−	
	e.g. confrontational trade policy				↕−
Collaboration	e.g. research partnerships	↕+			
	e.g. joint ventures		↕+		
	e.g. collective purchase			↕+	
	e.g. global governance efforts				↕+
Knowledge spillovers	e.g. labor mobility	↕S			
Value chain	e.g. design / production / installation		↕🔗		
Social acceptance	e.g. investors perceptions			↕@ —	↕@

5. Applications, limitations and potential developments of the framework

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 outcomes across activities and countries through the lens of sustainability. 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 25 provides the schematic diagram of the overall framework.

Figure 25: OoIF – Schematic diagram of the overall framework



Source: Own elaboration

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. 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.

We have also not contemplated explicitly the generation of jobs, which is often a critical concern for policy-makers. Increasing activity in the innovation system, particularly in activity P on "technology production and commercialization", will tend to translate into more jobs, but the quantity and quality of the jobs will critically depend on the type of technology, the part of the value chain captured, labor conditions, etc. We do not enter also into the discussion on how certain forms of technological innovation (mostly related to automation) may result in loss of jobs, as this does not seem to be a particular concern in the case of renewables –quite the contrary, they tend to be portrayed as job-generating technologies and evidence seems to support the claim (Ortega et al., 2015; Yi, 2013).

Moreover, we argue that there is potential to make much more explicit the connection between technological innovation and ecology, something largely missing not only in OoIF but in the innovation literature in general. In OoIF we just suggested a loop connecting production and adoption to signify the potential for circular approaches. However, we argue that for an approach aiming to understand the connection between technological innovation and sustainability, environmental factors should not only be considered as external to the technological innovation system, but embedded in it. After all, the way in which we produce and consume technology, as affected by knowledge and institutions (the full K-P-A-I system), is critical to determining the extent to which we create (or reduce) environmental impacts (Chertow, 2000). This could be a promising avenue for future work.

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[23]. 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.

Beyond the value of the representations to support discussion of ideas, we believe they could be useful tools to support diagrammatic reasoning for policy analysis and policy making. In our view, OoIF could help to:

- Clarify goals of innovation policy in terms of type of expected outcomes and consideration of directionality.
- 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 policy levers to tackle specific innovation-related activities or dynamics (complementary to technology-push/demand-pull and systemic policies) - 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 cross-national initiatives.
- 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.

Regarding its potential applications, 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 not necessarily restricted to the energy sector. Anyhow, further analysis would be needed to test the usefulness of the framework in the suggested applications. In the next section,

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[23] We have uploaded the three diagrams we have used to represent OoIF (-bb/-dw/-dx) in a platform that makes providing feedback very easy: https://redpen.io/pzec9b0ba97fdfcfd1. We will appreciate reading your comments there.

we undertake an empirical assessment for the cases of two renewable energy generation technologies.

Chapter 5_

Case study

An overview of global innovation in solar PV and wind technologies

Case study. An overview of global innovation in solar PV and wind technologies

In this Chapter, we turn to illustrate an application of OoIF consisting on a multi-country perspective of innovation processes for solar PV and wind technologies. We have chosen these technologies for a number of reasons: both have enough trajectory and data availability, both are widely acknowledged as the renewable solutions with the highest potential in the short to medium term, and both present different technological characteristics (such as degree of complexity, modularity and shippability) that allow for some comparison. We will focus on how OoIF can help to interpret two aspects of innovation processes that we have argued are not particularly facilitated by current IS frameworks and yet deserve consideration: the distribution of differentiated outcomes (1) and the impact of global dynamics (2).

1. Global distribution of innovation outcomes: an overview based on indicators

To explore how innovation outcomes have been distributed globally, we identify indicators that can provide some measure of OoIF's innovation activities (1.1), and represent and interpret their evolution across countries (1.2).

1.1. Identifying indicators for outcome-generating activities

The indicators we have selected include patent counts, exports, annual installed capacity[24] and electricity generation for each country and technology, and indexes on general/cleantech-specific innovation drivers and the overall level of CO_2 emissions in each country. These indicators have been selected to offer some measure of the degree of activity in OoIF's activities -even if these measures are partial and require careful interpretation, as we will explain next.

Patent counts, despite their widely acknowledged limitations (Johnstone et al., 2010), can reveal a portion of knowledge generation (activity K). Knowledge and capabilities are

[24] Studies looking at similar indicators, but with different problem framing and representation, and only for the case of solar PV include (Zheng and Kammen, 2014) and (Binz et al., 2017). (Pegels and Lütkenhorst, 2014) also used similar indicators to analyze Germany's performance in wind and solar PV as compared to other leading countries.

particularly difficult to capture in an indicator, as they include codified, uncodified and uncodifiable pieces, and their 'value' is very difficult to assess. Since patents are granted to protect inventions from commercial use without permission of the inventor, they often correspond to new knowledge with some market potential. As such, they also can be linked to some extent to technology production and commercialization (activity P). One issue with patents that may be particularly relevant to take into account for cross-country comparisons is the difference in patent breadth across countries (Dechezleprêtre et al., 2011).

Exports can be a measure of competitive production and commercialization of the technology (activity P). It is particularly useful to assess the degree of competitiveness of the produced technology, as competition in the global market often means only the most competitive products (in terms of costs and performance) get exported. It is not very useful however as an indicator of the level of manufacturing activity, as some countries may be producing mostly for domestic markets, and the ability to export may be determined by the characteristics of the technology such as modularity and shippability. This is a relevant consideration when comparing solar PV and wind: annual wind components exports represent an average of 8% of global investment in wind technology (which suggests most wind turbines are manufactured domestically), while annual solar panels exports represent an average of 91% of annual investment in solar PV (which suggests most installed solar panels have been manufactured abroad)[25].

Annual installed capacity can complement exports as an indicator of activity P, at least in two ways. First, for technologies such as wind in which most of the technology is manufactured domestically, annual installed capacity will be highly correlated with the level of manufacturing activity in the country. A subsequent question would be to analyze to what extent manufacturing activity is performed by national or foreign companies, what part of the value chain their activities in the country correspond to, or what is the level of technology transfer being realized. All these questions are relevant to understanding to what extent the country deploying the technology is being able to capture the benefits of the generated industrial activity. Second, beyond the production of the technologies, the deployment of renewable technologies involves some commercial activity linked to project development and execution, which is often carried out by domestic companies. In every case, beyond its possible links to activity P, annual installed capacity is a clear indicator for technology adoption (activity A).

[25] These figures are estimated with annual global investment data for wind (asset finance) and solar PV (asset finance + distributed) from BNEF (Frankfurt School-UNEP Centre / BNEF, 2016), and annual global exports from the UN COMTRADE database, in the period 2004-2013 (investment data for the period 2000-2003 was not available).

Electricity generation can work as an indicator for commercial activities that follow deployment, such as operations and maintenance activities (activity P), as it will be correlated with the total installed capacity in the country. However, we have selected it mostly as an indicator of use of the technology (activity A). The total amount of energy produced by these technologies offers a significant measure to understand the environmental impact of the technology, as it represents how much generation from other (often more pollutant) sources has been avoided.

For activity I, we have included two indexes on innovation drivers from the Global Cleantech Innovation Index 2012 (Cleantech-WWF, 2012), one for general innovation drivers (which measures general innovation inputs and entrepreneurial culture[26]), other for cleantech-specific drivers (which measures government policies, public R&D spending, access to private finance, infrastructure for renewables and cleantech industry organizations). However, we remain very aware of how these indexes can only provide a very rough measure of the countries' institutional context. Indeed, we consider institutional development as too complex to be represented in any single, quantitative measure that can be comparable in time and across countries. Case studies which explore the qualitative nature of institutions would be needed for a much richer understanding.

Finally, we represent CO_2 *emissions* as a relevant measure of the environmental impact created by the overall countries' energy provision (socio-technical system).

Overall, we suggest that interpreting the selected indicators through the lenses of OoIF can provide some basis to assess differentiated outcomes, and also reveal some ways in which they fall short in acknowledging difficult-to-measure, long-term and unintended outcomes. We have just suggested ways in which each of the indicators can be linked to activities K-P-A-I in OoIF. We summarize these connections in Table 13, including a qualitative valuation of the strength of the connection -or how representative the indicator is for the activity.

Table 13: Summary of selected indicators' relationship with OoIF and data sources

indicator	patents	exports	ann. installed cap.	elec. generation	inn. drivers index	CO_2 emissions
connection to OoIF						
connection strength	●○○ ●○○	(wind) ●○○ (solar) ●●○	(wind) ●●○ (solar) ●○○ ●●●	●●●	●○○	●●○
data source	OECD.Stat	UN Comtrade	BP Statistical Rev.	Resource IRENA	Global Cleantech	World Bank

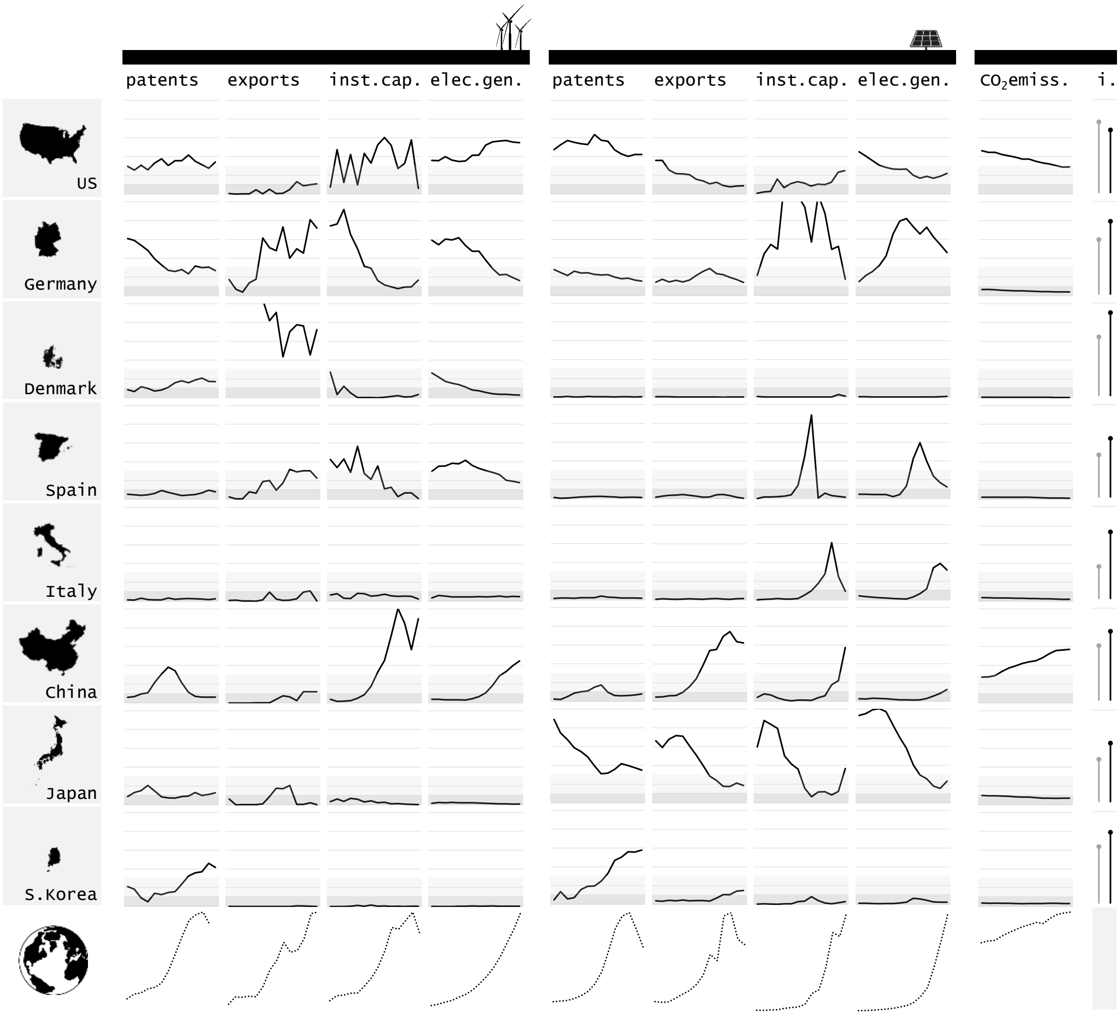
[26] These are taken from the INSEAD Global Innovation Index and the Global Entrepreneurship Monitor respectively.

1.2. Representing and interpreting the distribution of outcome-generating activities

As the basis to discuss the distribution of outcomes, Figure 26 provides a graphic overview of the evolution of countries' shares of global total on the selected indicators in the countries that were most relevant for the development of solar PV and wind technologies. The layout is a country-indicator matrix that allows for vertical and horizontal comparisons, with all graphs (except for the last row on global totals and the last column on innovation drivers indexes) showing countries' annual share on world total for a given indicator in the period 2000-2013. The vertical axis ranges from 0% to 50%, and shades correspond to 0-5% and 5-15% ranges. The last row represents the evolution of the global total for each indicator, normalized with respect to the series maximum in the considered period. Countries represented include United States, Germany, Denmark, Spain, Italy, China, Japan, and South Korea. The criterion to include countries has been to have at least 15% of global share in at least one indicator, in at least one year, in at least one of the technologies[27].

[27] Using shares with respect to global totals makes it easier for big countries to be in the picture. Per capita analysis could complement ours.

Figure 26: Overview of distribution of innovation activities by country for wind and solar PV technologies in 2000-2013



Source: Own elaboration

Columns correspond to indicators: patent counts, exports, annual installed capacity, electricity generation (first for wind, then for solar PV), CO_2 emissions and innovation drivers indexes. All but the last row and last column represent countries' global share as %, in a 0%-50% scale (shadows correspond to 0%-5% and 5%-15%). The last row represents global total, normalized with respect to series' maximum. The last column represents two indexes on general (in grey) and cleantech-specific (in black) innovation drivers indexes in year 2012.

A first impression when looking at Figure 26 is that the global distribution of innovation activities has been highly dynamic. In the 14-year period of analysis we see how shares on world totals move rather sharply, shifting from some countries to others. It is notorious for instance how Japan has moved from leading shares in solar PV in all indicators in the turn of the millennium to modest positions in recent years, or how China has moved from very little activity in all the indicators to becoming the largest market for wind turbines and the main exporter of solar panels just one decade later[28].

In some cases, the evolution of activities within a country can be easily interpreted as systemic. We see for instance how Germany was the largest adoption market for wind turbines by the turn of the millennium, accompanied by large shares of patenting activity, and that translated into a positive trend in exports over the following decade. Negative trends can also be realized, as in the case of solar PV in Japan, for which all knowledge, production and adoption activities have decreased evenly over the period of analysis.

In some other cases the evolution of indicators -if we keep the view within countries' boundaries- does not seem to exhibit a systemic behavior. Some countries may have experienced a sharp increase in one of the activities while experiencing no increase, or even a decrease, in other activities. This is the case for instance of South Korea, which has become a world leader in patenting activity while having very limited shares of production and adoption. It is also the case for Spain and Italy in solar PV: both countries became main adoption markets for solar panels in a very short period of time, which seemed to have no effect on their patenting or manufacturing activity[29]. Even for Germany, which has been the largest adoption market for solar PV for a longer period of time, the effects on patenting and export activity have been modest[30].

This is often read on a negative note, as countries may not be realizing the whole range of benefits they intended to achieve when implementing their RD&D or deployment policies. However, it can also be read positively, as some countries may be building in certain strengths without the need to develop the full range of innovation activities within their boundaries (Lund, 2009; Nahm, 2015);. We see for instance how the US has been particularly strong in patenting, while not so much in exporting or installing. Countries as different as Denmark and China have managed to develop leading positions in exporting wind turbines and solar panels respectively. European countries, especially Germany, have played a crucial role in opening up markets for these technologies.

What we may be intuiting here, and we will try to demonstrate in the following section by reviewing the evidence of global innovation dynamics (2), is that innovation processes for these technologies are still working as a system, but one that has become global.

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[28] For a discussion on China's technological innovation systems, see (Klagge et al., 2012) or (Gosens and Lu, 2014) for wind and (Huang et al., 2016) and for solar PV.

[29] See e.g. (Cai et al., 2016) for Italy and (Ortega et al., 2013) for Spain.

[30] See e.g. (Pegels and Lütkenhorst, 2014).

2. Global innovation dynamics: evidence from the literature

We turn now to explore the relevance of global dynamics in the distribution of innovation activities. We will do so reviewing the evidence found on the literature supporting the existence of the transnational connections proposed in OoIF-dx (and represented in Figure 24).

2.1. Technology transfer and knowledge spillovers

Perhaps the most notorious form of transnational connection in the context of technological innovation has been technology transfer. Many studies have found evidence of technology transfer through case studies (e.g. Pueyo et al., 2011), model simulations (e.g. Coe and Helpman, 1995) and econometric analysis (e.g. Lanjouw and Mody, 1996). Surveying a broad range of studies in the literature on technology diffusion, Keller (2004) founds evidence that the "*international dimension of technological change is of key importance for most countries*".

(Dechezleprêtre et al., 2011) provide one of the most comprehensive studies in the context of climate change-mitigation technologies (CCMT -including renewables) using patent applications in one country by inventors residing in another country in the period 1978-2005 as an indicator of TT. They found an average annual rate of increase in the number of climate-mitigation patents filed abroad during the 1990s of 8% -similar to the overall rate considering all types of technologies. Most of these transfers occur between OECD countries (73%), although transfer from OECD to non-OECD countries is greater in the case of climate-mitigation technologies than it is for overall technologies (22% compared to 16%) -of which China accounts for about three-quarters- and has increased in the last years of the analysis (1998-2005). For wind and solar they found export rates (defined as the share of inventions that are patented in more than one country) of 31% and 25% respectively.

In a similar but more disaggregated analysis, Haščič et al. (2010) assess bilateral transfer relations –i.e. technology transfer across pairs of countries-, with especial attention to transfers between Annex I[31] and non-Annex I countries. In the case of solar PV, they identify Japan, the US and Germany (in this order) as the main source countries, and China, Korea and Taiwan (again in this order) as the main recipient countries. In the

[31] The United Nations Framework Convention on Climate Change (UNFCCC) defines Annex I countries as the industrialized countries who have historically contributed the most to climate change. They include both OECD countries and "economies in transition" (the Russian Federation and several other Central and Eastern European countries).

case of wind, European countries appear as the main source, followed by the US, while China remains the main recipient, followed by Brazil, Korea and South Africa.

How has this cross-country technology transfer occurred in practice? Literature has traditionally emphasized three channels: licensing, foreign direct investment (FDI), and international trade. Case studies of renewable energy have shown how these channels have been relevant in the cases of wind and solar PV. For instance, licensing of Danish technology was at the birth of the Spanish wind manufacturing industry (Backwell, 2014). Wind companies in China, India and South Korea have assimilated foreign technology both through licensing arrangements and mergers and acquisitions - a form of FDI (Lewis, 2011). In the case of solar in China, importing manufacturing equipment -a form of international trade- seems to have been one of the key drivers for developing their PV industry (de la Tour et al., 2011).

We can also find evidence on how absorptive capacity, intellectual property rights and technological characteristics, as identified in OoIF-dx, have affected technology transfer in these technologies -e.g. see respectively (Binz et al., 2017; Branstetter et al., 2006; Watson and Sauter, 2011).

Knowledge has also diffused through less structured channels, in what we may call knowledge spillovers. Some studies that have tried to measure knowledge spillovers using patent citations (Jaffe et al., 1993; Jaffe and Trajtenberg, 1999; Peri, 2005) or patent data at the firm level (Branstetter, 2001) have suggested that knowledge spillovers occur mostly intranationally and not so much internationally, also apparently in the particular case of wind and solar PV technologies (Braun et al., 2010). However, other studies focusing on the international operations of multinational enterprises (Driffield et al., 2010; Ivarsson and Alvstam, 2005) and on the effects of labor mobility (Liu et al., 2010) suggest international knowledge spillovers may indeed be relevant. The case of the solar PV industry in China offers a prominent example of these relationships, with some studies highlighting the engagement in global networks interactions (Gress, 2015) or the return of internationally trained Chinese managers (de la Tour et al., 2011) as key drivers for its successful take-off.

Indeed, the rise of the solar PV industry in China has challenged conventional conceptualizations of technology transfer and industrial catching-up. Binz and Anadon (2016) describe the industry formation process undertaken in the Chinese PV sector as ‘industry transplantation’, emphasizing how Chinese entrepreneurs were able to access key system resources that were missing locally but available internationally, playing a highly proactive role and not just ‘receiving’ the technology. Moreover, technology transfer seems to have not been unidirectional but multidirectional, as both Chinese and overseas firms learned through cooperation in bringing the technology to large-scale commercialization (Nahm and Steinfeld, 2014). In this line, recent studies are pointing out that various forms of engagement in increasingly global innovation networks may be supplementing and surpassing conventional TT mechanisms (Lema and Lema, 2012).

2.2. International relationships of competition and collaboration

We have proposed in OoIF that we could characterize some of the relationships across countries as competitive or collaborative –recognizing that both types of forces coexist, and very often work entangled. The cases of wind and solar PV also provide some evidence on these relationships.

Regarding competition, the increasing concern on national competitiveness in policy discourses to support green technologies may well be taken as a manifestation of the relevance of competition across countries (Quitzow, 2013). This concept of national competitiveness often refers to the ability of national industries to compete on international markets and generate wealth for their countries, so it is really a reflection of the competitiveness of businesses based in the country. Indeed, competition is a key aspect to understand why some wind and solar PV companies succeed and some others fail (Cleantech, 2014). The case of solar PV offers a notable example of competition, as international market competition and international trade conflicts have resulted in the EU and US placing "anti-dumping" duties on the Chinese solar industry (Sun et al., 2014).

However, cross-country business operations can also take collaborative forms. Examples in the wind industry included the joint venture between Vestas (Denmark) and Gamesa (Spain) –which allowed Gamesa to commercialize Vestas' technology within the Spanish market (Lewis and Wiser, 2007), although later on Vestas and Gamesa became competitors-, or R&D cooperation between Chinese wind-turbine manufacturers and foreign design firms (Zhou et al., 2012). In the solar PV industry, BP Solar (Spain-based subsidiary of UK-based BP, defunct in 2011) engaged in a joint venture with India-based Tata (Tata BP Solar, currently Tata Power Solar), and also partnered with China-based SunOasis to build its position in the Chinese market (Pinkse and van den Buuse, 2012). International industry-led associations, such as the Global Wind Energy Council (GWEC) for wind and the Global Solar Council (GSC) for solar, can also be considered platforms for business collaboration.

Collaborative approaches for knowledge generation and exchange (activity K) have increasingly been recognized as means to deal proactively with knowledge spillovers and take advantage of their potential benefits. In the realm of renewables, there are some notorious examples of policy-led R&D collaboration, both bilateral and multilateral. One example of bilateral collaboration can be found in the Clean Energy Research Center (CERC), co-founded by the US and China, leveraging both public and private investment and implementing a governance framework conceived to facilitate cooperation while managing appropriability of inventions (Lewis, 2014). Among multilateral efforts, we can find the SET plan at the European level (Hervás Soriano and Mulatero, 2011), or international technology collaboration programs run by the IEA, such as the PVPS on photovoltaics (IEA, 2015). Still, the effects of international research collaboration on renewables seem to be rather modest, at least as reflected in patent fillings. Haščič et al. (2010) found that patent counts in CCMT that involved inventors from more than one country represented only 4.3% of their sample, with slightly higher rates of collaboration for solar PV than for wind technologies.

An example of a more comprehensive form of cross-country collaboration (potentially involving all activities K-P-A-I, although in practice focused mostly in A) can be found in the Clean Development Mechanism (CDM), introduced in the Kyoto Protocol. It can be considered collaborative because CDM projects aimed to be beneficial for both Annex I and non-Annex I countries involved: Annex I countries could reduce emissions more cost-effectively, while non-Annex I countries were able to access cleaner technologies. CDM seem to have been relevant for the diffusion of wind in some countries, particularly in China and, to a lesser extent, in India (Timilsina et al., 2013). On the contrary, solar PV has had very limited presence in CDM projects (Seres et al., 2009). Overall, CDM seem to have had positive effects not only in the diffusion of the technology, but also in technology transfer of both equipment and know-how (Schneider et al., 2008). However, the rate of CDM projects involving TT seems to vary largely by country: according to (Dechezleprêtre et al., 2009b), 12% for India, 40% for Brazil, 59% for China and 68% for Mexico –which together constitute 75% of CDM projects. The technology used in CDM projects originated mostly from Germany, the US, Japan, Denmark and China (Murphy et al., 2015).

Other international technology-oriented agreements to address climate change have included the Global Environment Facility (GEF) or the Asia Pacific Partnership on Clean Development and Climate (APP) (de Coninck et al., 2008), and very recently climate change and sustainable development negotiations have resulted in new collaborative initiatives being launched.

Mission Innovation[32], announced during COP-21 in Paris 2015, has gathered 22 countries and the EU to pledge to double public R&D investment in energy R&D over five years, in an effort to *"reinvigorate and accelerate public and private global clean energy innovation with the objective to make clean energy widely affordable"* (Mission Innovation member countries, 2015). Countries have also pledged to take actions for information sharing,

[32] http://mission-innovation.net/

innovation analysis and roadmapping, joint research and capacity building, and business and investor engagement (Mission Innovation member countries, 2016). This idea of joining public and private efforts has been present from the launch of the initiative, with the Breakthrough Energy Coalition[33] gathering private investors that commit *"to put truly patient and flexible risk capital to work in service of a long term commitment to new technologies"* (Breakthrough Energy, 2017).

The recently approved Sustainable Development Agenda has also emphasized the role of collaboration, even including *"partnerships for the goals"* as one of the Sustainable Development Goals (SDG 17) (United Nations, 2015b). To facilitate technological innovation in particular, it has announced the Technology Facilitation Mechanism[34], which aims to serve as a collaborative, multi-stakeholder platform for *"the sharing of information, experiences, best practices and policy advice"* (United Nations, 2017). The agenda also included the pledge to fully operationalize a *"technology bank and science, technology and innovation capacity mechanism for least developed countries"*, but does not provide any details on how it could be implemented (Colglazier, 2015).

In any case, how much collaboration these recent initiatives will be able to generate, and how much impact that collaboration will have on spurring technological innovation in clean technologies, is yet to be seen.

2.3. International value chain relationships

Value chains for both solar PV and wind technologies have become international. Evidence suggests that 65-70% of the value creation of these technologies corresponds to core components (which may be produced across various countries), while system installation (mostly a local activity) represents about 15-30% of the total value (Lund, 2009).

In the case of solar PV, Zhang and Gallagher (2016) provide a detailed account of the globalization of its value chain, with particular focus on the role of China. They identify the global top 10 actors in different value segments along the solar PV value chain and observe how the R&D segment is led by patent assignees from Japan, the US and South Korea; the capital equipment and polysilicon segments by firms from Europe, the US, and Japan; the applied materials segment by firms from Germany and the US; the manufacturing of both cells and modules by firms from China; and the balance of system

[33] http://www.b-t.energy/

[34] https://sustainabledevelopment.un.org/TFM

and final deployment segments by firms from Europe (as most of the installations have been carried out in Europe).

Moreover, some studies have noticed the value distribution between the largest PV manufacturer (China) and the largest installer (Germany), pointing out that while most manufacturing activity has moved to China, Germany has produced most of the manufacturing equipment (Grau et al., 2012) and maintains robust positions in the supply of mechanical PV equipment within a globalized PV value chain (Dewald and Fromhold-Eisebith, 2015). Kirkegaard et al. (2010) interestingly add to the discussion the consideration of job creation, estimating that in 2009 around 60% of the jobs related to small-scale installations and 40% of the jobs related to field installations were created in the local, downstream installation segment. If operation and maintenance jobs are included, then they estimate more than half of the jobs created by the solar PV industry are not "outsourceable".

In the case of wind power, Lund (2009) notes how turbine manufacturers often keep control of strategic parts of the value chain -e.g. rotor blades and controllers- whereas other more standardized components -e.g. gearboxes and generators- get outsourced to global component manufacturers -with some exceptions, such as India's wind manufacturer Sulzon, which is a fully vertical integrated company.

This evidence supports the claim that understanding value chain relationships across countries is a key consideration to assess innovation outcomes.

2.4. International trends in social acceptance/support

We suggested in Chapter 4 how the adoption of a technology and institutional developments co-evolve in processes that may have an international dimension. In particular we proposed that trends in the attitudes of users, investors or policy-makers across countries will affect social acceptance/support (in all its socio-political, market and community dimensions).

International policy diffusion and policy learning constitute a source for the creation of these trends. For instance, Szarka (2006) discusses how global and European-level policy developments (e.g. 1992 Rio world conference, 1997 Kyoto protocol, and several Environmental Action Programmes in the EU) led to policies in support of renewables in countries such as the UK, Denmark and France. Also, even when there have been very limited international energy policy efforts (Hirschl, 2009), policy and regulatory approaches for the support of renewables have tended to converge to mechanisms that have proven successful in leading countries (Lipp, 2007).

Investors' choices in global financial markets also affect the creation of these trends, as financing is a critical aspect for the installation of renewables. For instance, Masini and Menichetti (2012) have studied how *"the investors' a-priori beliefs, their preferences over policy instruments and their attitude toward technological risk affect the likelihood of investing in RE projects"*. Others have studied how the design of renewables support through particular policy instruments may affect private investors' decisions (Bürer and Wüstenhagen, 2009; Dinica, 2006). Overall, we can see how global trends in renewable energy investment have supported a significant increase in global renewable power capacity (Frankfurt School-UNEP Centre / BNEF, 2016).

Although consumer or community attitudes are very important for the adoption of solar PV (Faiers and Neame, 2006) and wind technologies (Breukers and Wolsink, 2007), we could expect international dynamics playing a much less significant role here than for policy and market trends.

Finally, we would like to acknowledge the role of multilateral institutions in generating these trends across countries. The International Energy Agency (IEA) and, more recently, the International Renewable Energy Agency (IRENA) constitute a good example. The IEA has offered for some time a focal point to understand the international evolution of both market and policy trends for renewables and other energy technologies (OECD/IEA, 2004). Since 2010, the International Renewable Energy Agency (IRENA) has aimed to offer a platform for collaboration and repository of resources to promote the widespread adoption of renewable technologies (IRENA, 2016). With the lenses of OoIF, we could locate IRENA as an international catalyzer for increasing the social acceptance of renewables.

3. Synthesis of the case study

In this chapter we have presented an analysis of the distribution of innovation outcomes across countries for the case of wind and solar PV technologies from the turn of the millennium, and collected evidence from the literature on how international dynamics have affected the innovation processes of these technologies.

This has allowed us to illustrate the relevance of the perspective provided by OoIF to interpret innovation developments for these technologies. First, by showing the importance of differentiating innovation outcomes and appreciating their distribution globally -as we see 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 -as evidence from the literature demonstrates how innovation processes for both wind and solar PV have largely been affected by cross-national dynamics such as technology transfer, knowledge spillovers, international competition/collaboration, value chain relationships and international trends in social support.

Overall, we conclude that OoIF has provided some useful basis to articulate the analysis of the distribution of innovation outcomes across activities and countries, and to identify relevant cross-national relationships, so as to offer a novel perspective on the empirical evidence of innovation processes of wind and solar PV: one that emphasizes that countries may not realize all innovation-related outcomes for a given technology (or at least not all of them to the same extent) and the importance of considering innovation dynamics beyond countries' borders to understand the outcomes they are able to realize.

Chapter 6_

Discussion

Global sustainability challenges and countries' quest for prosperity: can energy innovation policy respond to both?

Discussion. Global sustainability challenges and countries' quest for prosperity: can energy innovation policy respond to both?

In this chapter we discuss the policy implications of the analysis developed in the previous chapter, Chapter 5. We first point to the apparent tension between national interests and global challenges (Section 1) and then develop the policy implications from the perspective of a country (Section 2) and from a global perspective (Section 3). Finally, we describe some ways in which OoIF could be applied in innovation policy-making (Section 4).

1. National interests, global challenges – framing the purpose of innovation policy strategies

Through the case studies of solar PV and wind technologies, and using OoIF to articulate the analysis, we have seen how innovation-related outcomes for these two technologies have been distributed differently across countries in highly dynamic processes where transnational dynamics have played a crucial role. From the perspective of a country, this means some countries may not be realizing the benefits they intended to achieve when setting up their RD&D and deployment policies on renewables. However, from a global perspective, it may be precisely the complementarity of contributions from different countries what has allowed both technologies to experience significant improvements in performance and cost that have moved them towards competitiveness with other technologies -which is indeed good news for climate change.

Thus, should we contemplate 'innovation leakages' as a threat to national competitiveness or as welcomed contributions to solve a shared challenge? The answer is far from straight.

On the one hand, just accepting national leakages as a contribution to solve a global challenge -although ideal from the perspective of solving climate change, and perhaps essential if we acknowledged decidedly the threat of climate change in all its scale- does not seem realistic in our current sociopolitical context[35]. National policies to support renewables need to be based on social acceptability that ensures political legitimacy for sustained efforts. If social acceptability is not granted -as people perceive their interests are not being protected-, policy initiatives in support of renewables bear the risk of backlashes that would ultimately be detrimental to the development of these technologies.

On the other hand, pursuing national interests that disregard global interests is very likely to be a failed strategy even from the perspective of the country, especially when we move from short-term to mid- and long-term considerations. The case of climate change is one of particularly large implications: failing to mitigate it will probably involve large costs in adaptation and losses in climate-related damages (Stern, 2007). We could also argue that failing to participate in solving global challenges could involve missed opportunities in terms of building social capital, namely in the form of cooperative alliances.

In any case, the challenge of climate change urges us all to rethink our policy approaches (from the policy-makers' side) and policy expectations (from the people's side). If we are to avoid temperature increases beyond 2ºC, we need massive action on a global scale. Partial efforts by a small number of countries -although probably essential as first steps for a larger scale transition- would only buy us some time in our chase to curve down emissions. Indeed, if we think on the urgency of the transition to low-carbon pathways at a global scale, we could argue that we do have a 'green race'[36], but one that it is not against other countries, but against time.

From this perspective, the challenge is then how we can make the global innovation system for renewables work as effectively as possible while articulating viable paths for countries. Or from the perspective of countries: how countries can better design their policies affecting energy innovation in a way legitimately aligned with their national interests while contributing effectively and sufficiently to global efforts to mitigate climate change. In the following sections we will discuss how policy can respond to this challenge, first from the perspective of countries (Section 2), then from a global perspective in the context of climate change negotiations (Section 3).

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[35] Even less so in view of recent sociopolitical developments in the Western world, in which we are witnessing a revival of political discourses that portrait national interests as confronted with international cooperation.

[36] The 'green race' rhetoric emerged in the 1990s referring to the countries' chase of competitive advantage in low-carbon technologies (Voituriez and Balmer, 2012).

2. Policy implications for countries

For countries to respond to the challenge as just put forward, they can prioritize those spaces where their national interests can be aligned with global interests, while we work in moving national interests closer to what is globally desirable -namely, global sustainability. The former asks for strategic approaches to innovation policy-making (2.1), and proactive engagement in the global innovation system (0); the latter for broadening out our current interpretations of policy success (2.3) and for cultivating well-grounded social acceptance (0).

2.1. Look for technological areas and segments of the value chain where you can better contribute to create value

The analysis presented in Chapter 5 has shown how, in the case of renewables, transnational innovation dynamics have become very relevant. Countries assuming that a focus on internal innovation dynamics together with a combination of technology-push/demand-pull policies will bring about successful innovations within their boundaries may well discover global developments disrupting their expectations. This realization supports our initial claim that policy-makers should aim for a strategic approach to innovation policy-making, particularly one that is able to respond to the unfolding global innovation dynamics.

This requires acknowledging the position of the country in the global innovation landscape and leveraging its capabilities accordingly, aiming to find those technological areas and segments of the value chain where they can better contribute to create value - so both national and global benefits can be realized.

The resulting "strategy" is likely to be neither fully deliberate nor fully emergent, as strategic management has suggested for organizations (Mintzberg and Waters, 1989). On the one hand, the urgency of the need to transform socio-technical systems towards sustainability means entirely emergent strategies are not likely to deliver a large-scale transition in time. On the other hand, the complexity of innovation processes, increased in the global context, means entirely planned strategies are not feasible. This in turn means policy-makers should be prepared for a strategic approach to innovation policy-making that works simultaneously and recursively between formulation and implementation, and which combines a sense of direction with the space for allowing innovation processes to emerge.

2.2. Engage proactively in the global innovation system

Strategic policy-making in the global innovation context also requires engaging proactively, and not just reactively, in transnational dynamics and global innovation networks.

Indeed, we have seen how evidence is pointing out to the opportunity for countries not necessarily to build their own full innovation system *around a certain technology*[37] –as has normally been the argument- but to integrate into the global innovation system taking advantage of their comparative advantages (Ball et al., 2017). The "entry point" into the global innovation system may be different for countries, depending on their preexisting capabilities and their distinctive efforts.

Engaging proactively in the global innovation system means exploiting policy options beyond the traditional technology-push/demand-pull and the systems framings, incorporating policies that facilitate technology transfer or collaboration in global networks. We propose that OoIF can provide some basis to articulate strategic thinking for policy-making, particularly by facilitating the understanding of ways in which a country's innovation system is interconnected with other systems, in an overall global innovation system.

2.3. Broaden our interpretation of success of innovation policies

Regardless of how strategic policy-makers aim to be in setting up their innovation policies, we need to acknowledge that their (our) expectations cannot be realized entirely, as innovation processes are full of uncertainties, even more so in a globalized context. This requires also a shift in the way policy-makers themselves, and people in general, perceive the outcomes of innovation policy efforts, particularly when they tackle technologies that could help us overcome relevant challenges, as in the case of renewables.

[37] Note that this does not contradict the idea of having a well-functioning innovation system at the aggregated level of all technologies and sectors. At the aggregated level, it will still be important for a country to build a strong national innovation system, as different innovation activities contribute in complementary ways to building welfare-improving capital. In this respect, it is particularly important to bear in mind the central role of human connecting dynamically all activities: all activities can contribute to the building of knowledge and capabilities, and all activities in turn need them to be realized.

How do we define success/failure of innovation policy-making? Very often the criteria behind these tags relies on evidence of development (or not) of a competitive national industry that produces and commercializes the targeted technology. Yet, we have seen how the extent to which countries are able to achieve industrial and commercial activity as a result of their policies in support of renewables may vary greatly, both across countries and in time, and how we need to treat 'industrial and commercial activity' in a more nuanced way to be able to grasp the outcomes resulting from differentiated positions in the technological value chain -it is not only about manufacturing, as some debates seem to imply. Moreover, applying OoIF, we saw how we could also consider outcomes related to knowledge generation and capabilities building, to the improved environmental performance of the installed technologies, or to the institutional developments that could enable further innovation.

We therefore suggest that focusing just on short-term industrial/commercial outcomes of a given technology constitutes quite a narrow interpretation of innovation outcomes. How we interpret success of innovation policy depends on the level of aggregation of technological efforts (single technology versus portfolio), time horizon (short-term, static versus long-term, dynamic effects), breath of outcomes (single criteria -often of an economic nature- versus multiple, more diverse criteria), geographical scope (within borders versus abroad), and consideration of directionality (contributing to advance in the preferred direction?).

We argue that, in the context of innovation policy-making towards sustainability, we probably need to broaden out our interpretation of innovation outcomes in all these dimensions, and that OoIF can provide some basis for doing so: we could aim to judge innovation efforts ultimately for how they -collectively- contribute to build welfare-generating knowledge-production-consumption-institutions systems that evolve through conducive-to-sustainability pathways.

Why would this contribute to relax the apparent divide between national and global interests? If our policy discourses were ingrained in such a broad interpretation of innovation success, we would overcome partial interpretations -such as "who gets the manufacturing"- that exacerbate the perception of competing interests among countries. While we could not expect all countries benefitting from manufacturing a given technology simultaneously, there should be space for every country to work towards building different but complementary welfare-generating innovation systems.

2.4. Cultivate well-grounded socio-political acceptance/support

In any case, broadening our policy discourses needs to go hand in hand with an evolution in people's perceptions. Policies are meant to improve people's wellbeing, but the way people interpret what contributes or fails to contribute to their wellbeing is highly subjective and built through the complex evolution of culture, beliefs, narratives… Innovation policy-making cannot ignore this, but rather aim to build on well-grounded socio-political acceptance/support that ensures legitimacy for sustained policy efforts.

This probably requires especial attention to the process of policy-making, to make it inclusive and transparent, and also prone to learning and adaptation. We argue that, by providing some basis to interpret the outcomes of innovation -which allows for multiple interpretations of innovation success, depending on the importance attributed to benefits from advances in knowledge/production/adoption/institutions, and to directionality- OoIF could help in better defining, communicating, discussing and readjusting policy expectations, in a process that could contribute to building socio-political support.

However, this dynamic interpretation of socio-political support bears the risk of failing to sustain innovation efforts long enough to achieve positive results, unless there is a sense of direction provided by some shared vision of where we would like to head towards. We anticipated this idea when discussing the building blocks of OoIF: innovation policy with deep implications in the transformation of our socio-technical systems should rely on the building up of shared visions that enable the consistency and endurance of policy efforts. Note the building up of these shared visions is not only the responsibility of policy-makers, but policy-makers can nonetheless play a critical role in opening up the spaces to generate them through stakeholder engagement.

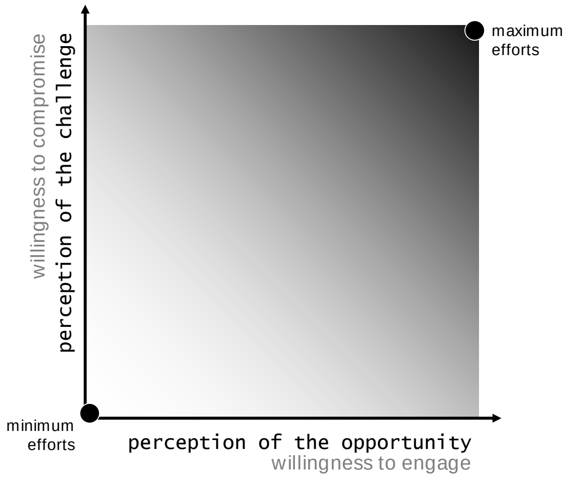
3. Policy implications for global governance

3.1. The need to intensify innovation efforts

Despite strong claims for a low-carbon energy transition, both on the grounds of the need to shift to low-carbon development paths to avoid catastrophic consequences and on the opportunity to generate 'green growth', and despite some notorious developments in the realm of renewables and other low-carbon technologies, the reality nowadays is that we still do not seem to be immersed in a global transition of the depth and scale claimed -or perhaps we are only in its infancy and not yet sure of how it will evolve[38].

Why are we in this situation? One possible explanation could be that we -collectively- don't believe strongly enough in either the challenge or the opportunity, or both, which affects our willingness to compromise and to engage proactively in the transition (see representation of this proposition in Figure 27). And the reason for not being "full believers" probably has to do with the fact that there are high degrees of uncertainty involved -both on the scale of (positive & negative) impacts and on how they will be distributed- and that their effects would be seen on a longer time scale or a broader spatial scope than what most of our institutions are currently designed to cope with.

Figure 27: Proposition of how efforts for the low-carbon transition depend on perceptions of challenge and opportunity



For many, the take-off of the transition will only occur when we get low-carbon technologies to be competitive, because then it is not a question any more of perceptions and assessment of long-term impacts: low-carbon technologies would much more easily become the preferred option for new installations, and we could expect them finally breaking the current lock-in to diffuse massively.

But to get there we need to get moving towards "maximum efforts" (Figure 27) now, to make those innovation efforts that can ultimately take us to the competitiveness of these technologies. And not only for the particular goal of achieving widespread low-carbon power generation, but also to manage to build the institutions that would get us better

[38] Indeed, those that have studied energy transitions agree on how they represent lengthy processes (Grubler, 2012).

prepared to cope with other pressing large-scale, long-term environmental challenges[39]. Indeed, many of the Sustainable Development Goals (SDGs) put forward in the recently approved global agenda to guide development towards 2030 urge us to deal with challenges of such nature (e.g. SDG 14: "life below water" or SDG 15: "life on land").

3.2. The role of collaborative approaches in international climate change negotiations

One way to keep us moving while building global social capital is to find collaborative ways to handle the uncertainty involved in innovation, increasing our willingness to engage and compromise by sharing risks and benefits. We have seen how the role of international collaboration in advancing innovation in renewable technologies has been rather limited so far, but how recent efforts seem to be advancing in this direction. We discussed Mission Innovation and the Technology Facilitation Mechanism as collaborative initiatives currently aiming to make technological innovation work towards more sustainable energy futures.

Some may dismiss the potential for collaboration as unnecessary (or even counterproductive), as they believe it is competition and not collaboration what can ultimately bring down the costs of low-carbon technologies. However, although competition has a role to play (and indeed we have treated competition and collaboration as coexisting, intertwined forces in our framework), there is wide agreement in the literature that business-as-usual market-based competition cannot deliver the needed transition to cleaner technologies due to a combination of market failures, behavioral aspects and socio-technical lock-ins (Grubb et al., 2015). As the public sector intervenes to spur the transition, other logics beyond competition can –and probably should- be encouraged. Again, this is particularly relevant when we think that only by mobilizing efforts globally we can aim to overcome a global challenge as the one posed by climate change. When dealing with the challenge of climate change, we just cannot accept 'winners' and 'losers' as resulting from competitive forces, as we may in other fields: if we don't win all together, we all lose.

Some others may dismiss the potential for collaboration to mitigate climate change as ineffective, as it requires large, complex efforts of negotiation and coordination that maybe could be avoided by promoting renewables or other low-carbon technologies on

[39] As (Bass, 2009) expressed it, there is still some *"'wiring' needed to link governance of national and global economies with governance of the environment and natural resources".*

the grounds of interests that resonate more with the immediate interests of communities, such as avoiding local pollution or increasing energy security. Of course these are legitimate motivations to support renewables, and can prove more suitable in communities where the debate about climate change has become polarized. However, this approach is likely to deliver partial results, as focusing on local impacts may neglect the need to transform energy systems operating outside the localities (e.g. air and sea transport), and only those communities with access to cleaner technologies would be able to install them (which may leave out many communities without the capabilities to do so). Again, when dealing with the challenge of climate change, we need a transformation so broad and deep that partial efforts will not be enough.

But very importantly as well: neglecting climate change as a driver for innovation "because it is far away from the immediate interests of the community" may prevent us from advancing our narratives to appreciate the global scale of some of our challenges ahead. We need to recognize that we all share a single planet, that we have created some serious threats to it, and that we need collective efforts to overcome them. Only on these grounds can we build the (formal and informal) institutions that could allow us to work collectively to overcome global challenges.

Recently, Harari (2015) has defended that *homo sapiens* dominates the world because it is the only species that can cooperate flexibly in large numbers. From this perspective, it is our ability to cooperate what has allowed us to reach a stage of development that is positively impressive in many ways, but that also has created very important challenges that threaten sustainability. Studies on the management of the commons have proven that we have been able to develop institutions to achieve sustainable uses of local or regional common resources (Ostrom, 1990). Could we use our ability to cooperate to deal with global challenges too?[40]

[40] See (Smith, 2017) for an approximation on how we could apply at a global scale what we have learned from the management of the commons.

Box 10: An example of collaboration in nature
– could it inspire international collaboration for climate change mitigation?

On how penguins collaborate to survive the cold

How do penguins survive the freezing winter temperatures in Antarctica? Apparently, the answer has much to do with social huddling. Those that studied the behavior of huddles of emperor penguins found out that the huddling is not static, but dynamic: penguins rotate positions to move from the cold outside the group to the warmer inside, which "*enables all breeders to get a regular and equal access to an environment which allows them to save energy and successfully incubate their eggs during the Antarctic winter*" (Gilbert et al., 2006; Nature on PBS, n.d.).

For penguins, the collaborative dynamics in the huddling are a matter of survival. If penguins remained static in their positions, those in the outside would probably not resist the severe climate, and as the penguins in the outside died, the survival of the penguins inside would be threatened. They have come up with a social solution in which they are willing to accept partial loses (being exposed to the colder temperatures at the group's periphery for some time) so greater wellbeing for the overall group can be realized -which indeed becomes the most beneficial for individuals too, particularly when considering the longer term perspective.

Could there be a 'penguin solution' to climate change? Could countries find solutions that allow the risks and benefits of the transformation to be shared more equitably among them for greater global good -which in turn would be the most beneficial for countries themselves?

In short, even if we acknowledge the role of market competition for delivering innovation, and the role of other drivers other than climate change to spur the transition to cleaner technologies, we join others[41] in suggesting that international collaboration for climate change mitigation should play a prominent role. In doing so, we could not only make the global innovation system deliver the widespread technological advances that we need more effectively, but also build the social capital that will enable us to deal with our common challenges in the future.

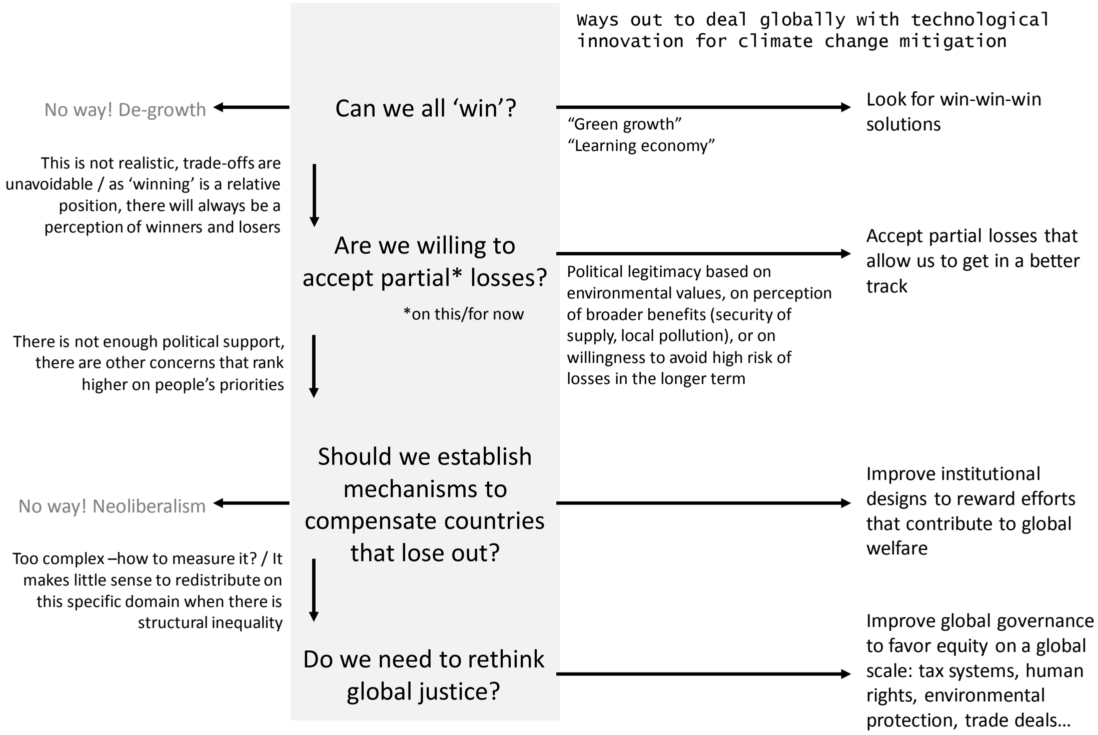
This would have profound implications for the future of innovation policy, which will need to incorporate the consideration of multilateral relationships. Indeed, according to (Smith, 2017), *"how such supranational policy is conceptualized and organized may well be the most important of all future challenges"*.

3.3. What type of collaboration do we mean?

When we claim that we need collaborative approaches to deal globally with technological innovation for climate change mitigation, what type of collaboration are we referring to? Intrigued by this, I asked myself a chain of cascaded questions: Can we all win? If not, should we be willing to accept partial loses? If not fully, should we establish mechanisms to compensate countries that lose out? And if that is the case, shouldn't we need to go beyond 'energy innovation' matters and rethink global justice in general? Answers to these questions may reflect a combination of objective and subjective views, be based on a combination of evidence and perceptions fed by data and narratives, and be affected by political standings and ethical underpinnings. Figure 28 summarizes the possible range of answers I came up with, trying to reflect a variety of viewpoints.

[41] King et al., 2015; Kirkegaard et al., 2010; Newell et al., 2011; Smith, 2017…

Figure 28: What do we mean by collaboration among countries? Exploring some possible answers



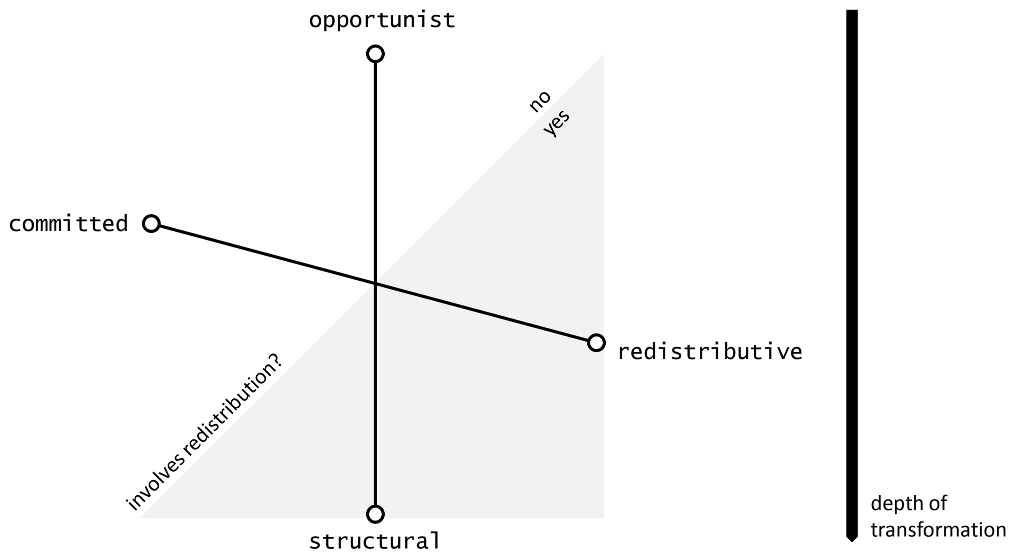
Source: Own elaboration

Answers pointing to the right [42] in Figure 28 provide possible approaches to collaboration. Arguably, they are ordered from the easiest to the most difficult, in terms of the degree of commitment and intervention needed. The first one would be looking for solutions in which all countries can win -what we could call *opportunist collaboration*. If that is not feasible, if we have exhausted all the win-win possibilities, or if countries are deeply committed to a sustainable transformation, they may be willing to accept partial losses that allow for global progress to sustainability -what we could call *committed collaboration*. If that is not feasible, or only to some extent, we may consider finding ways to compensate those countries if their efforts result in loses for the country but generate welfare globally -what we could call *redistributive collaboration.* However, that would be a very complex endeavor -how would we measure efforts and contribution to global welfare? And perhaps more importantly, would it make sense to redistribute on a specific domain -such as energy innovation- when there is structural inequality among countries? Perhaps we need to rethink global justice and promote equity-enhancing structural changes -what we could call *structural collaboration*.

[42] Answers pointing to the left just aim to suggest viewpoints that would tend to reject the type of approach suggested in the same-level arrows pointing to the right.

We sum up these four collaboration approaches we have identified -opportunist, committed, redistributive and structural- in Figure 29, categorizing them according to whether they contemplate or not redistribution, and by the depth of the transformation they involve.

Figure 29: Suggested collaboration approaches, categorized according to consideration of redistribution and depth of transformation



Source: Own elaboration

We suggest that the context of climate change negotiations may provide a fertile ground to try out collaborative approaches in these four coordinates, from the 'easiest' opportunist forms of collaboration to the 'deepest' structural forms of collaboration.

4. Innovation policy making with OoIF

In our view, the way in which we depict (literally -in graphs, or figuratively -in our minds) innovation processes largely conditions the type of policies we are able to imagine and implement. In Chapter 3 we saw how, in neoclassical approaches, innovation processes tend to be depicted as input-output relationships, and suggested policies tend to be framed as technology-push/demand-pull. In innovation systems approaches, innovation processes tend to be depicted as interconnected elements that interact forming a system, and suggested policies tend to refer to improvements in the structure and/or the interconnections of the system. In technological transitions approaches, particularly in the representation offered by the multi-level perspective, innovation tends to be depicted as the process of destabilization and reconfiguration of a socio-technical system, and suggested policies tend to propose ways to enable, facilitate or promote that destabilization and reconfiguration. By offering a new way to depict innovation processes, we believe OoIF opens up some space for novel policy approaches.

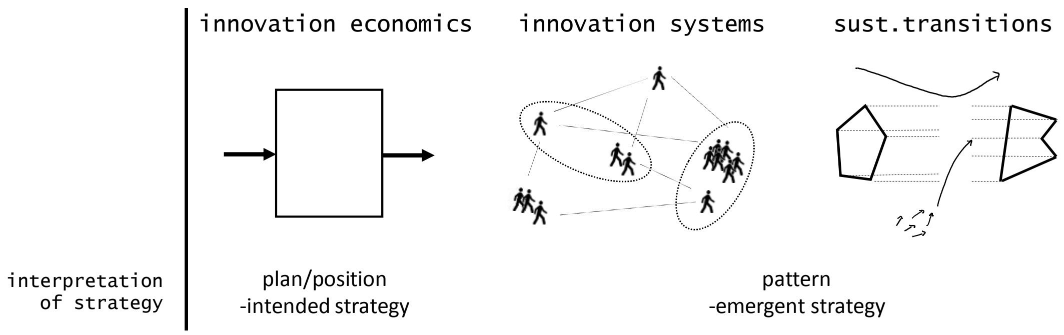
In this section we discuss some possible practical applications of OoIF to support innovation policy making.

4.1. Strategic thinking

OoIF has been conceived as a tool to support strategic *thinking* -not so much strategic *planning*. It may facilitate the understanding and discussion of complex innovation dynamics, and the articulation of innovation goals. However, we already suggested how energy innovation policy strategy needs to be conceived as partly intended, partly emergent, and move recursively between formulation and implementation.

We could argue that different innovation perspectives may be prone to support different interpretations of strategy. In particular, we would like to argue that neoclassical perspectives are more prone to conceive intended strategies, whereas evolutionary perspectives (innovation systems and transitions) are more prone to conceive emergent strategies. We illustrate this proposition in Figure 30. As OoIF draws from the three perspectives, we think it could provide a balanced basis for strategic thinking.

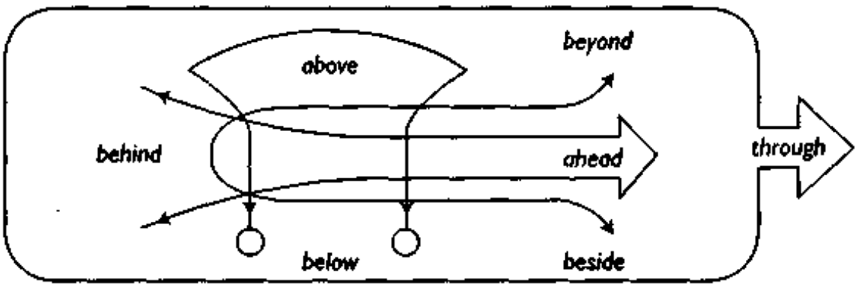
Figure 30: How innovation perspectives interpretation of strategy



Source: Own elaboration

One way of interpreting strategic thinking is as 'seeing': seeing through, ahead, beyond, above, behind, below, beside the organization (Mintzberg et al., 1998) – see Figure 31 for an illustration.

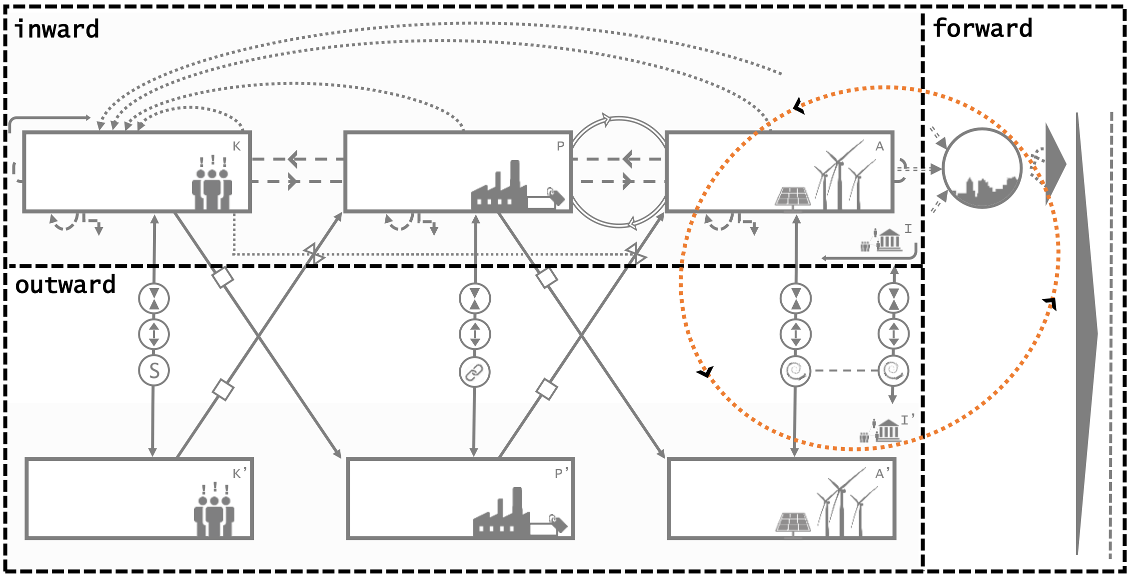
Figure 31: Illustrating "strategic thinking as seeing"



Source: (Mintzberg et al., 1998)

OoIF encourages strategic thinking by 'seeing' in three directions: forward, inward and outward the innovation system – see Figure 32 for an illustration. By looking forward, we can clarify the horizon and the vision of the socio-technical system we would like to move towards. By looking inward, we can understand the relative performance in the different innovation-related activities and how well they are interconnected to work systemically -strengths and weaknesses. By looking outward, we can interpret the interactions with other countries' innovation systems and identify existing and potential relationships of competition, collaboration, technology transfer, etc. -threats and opportunities.

Figure 32: Strategic thinking with OoIF: forward, inward, outward look

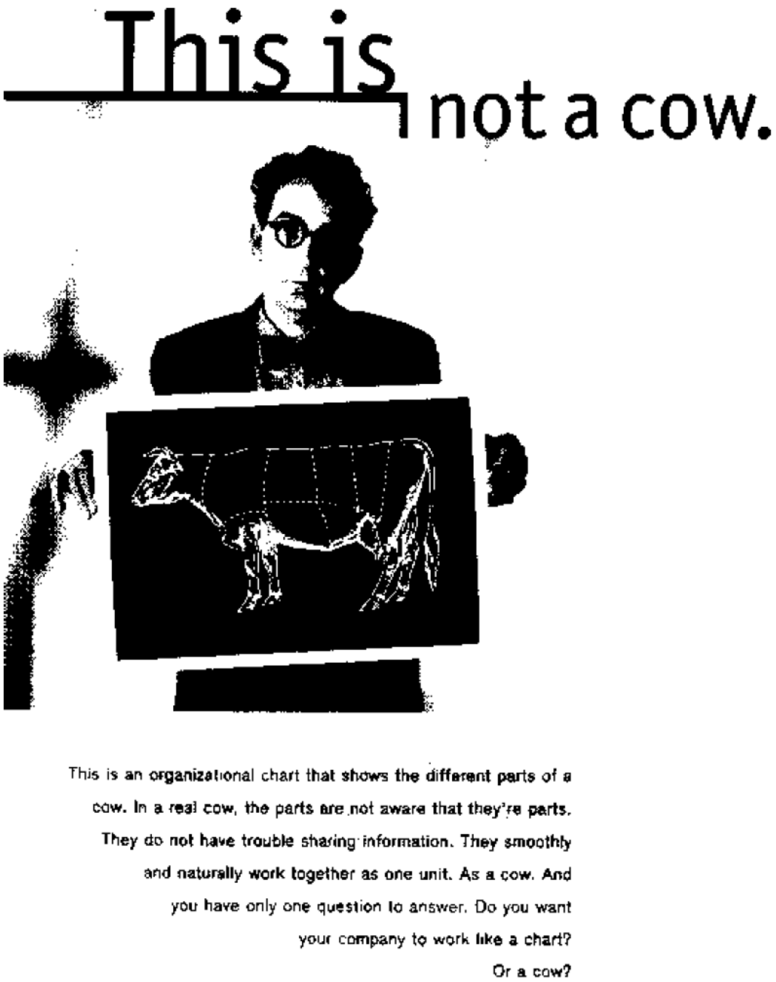


Source: Own elaboration

This analysis/interpretation should not be piecemeal -we should aim instead for an integrated analysis in which we iterate between the forward, the inward and the outward perspective. Indeed, the insights gained from one of the perspectives could take us to challenge previous insights from another perspective: for instance, the realization that international dynamics could threaten some current strengths in our innovation system may take us to reconsider our vision for the future and our consideration of internal capabilities.

To remark this idea, we can use a famous metaphor in the management literature, illustrated in Figure 33. This figure shows the image of a cow with its different parts (rib, sirloin, etc.) and uses it to describe the limitations of organizational charts: *"in a real cow, the parts are not aware they are parts, (...) they smoothly and naturally work together as a unit"* (Mintzberg et al., 1998). Similarly, we need to remain aware how the elements we have used to build OoIF may provide useful units to interpret reality, but need to be interpreted as a complex whole.

Figure 33: How a real cow is more than its parts



Source: Anderson & Lembke NY, in (Mintzberg et al., 1998)

This may be indeed the biggest challenge in using OoIF, as of other frameworks to support strategic thinking. As expressed by (Moncrieff, 1999), *"strategy appears to be a holistic, continuous process: which we disintegrate through theories, models, frameworks and labels, in order to understand and talk about; but which we have trouble re-integrating as an interactive and interdependent whole"*.

Indeed, strategy requires a component of judgement and intuition that cannot be incorporated into a process or framework. That is why, for many, strategy is much more than analysis: it is a creative act!

4.2. Integration of policy approaches

OoIF can also provide some basis to interpret how different innovation policy approaches come together.

We argue that our interpretation of what innovation policy is about has enlarged and shifted in focus:

from very narrow conceptualizations in which innovation was only about moving from basic knowledge to industrial applications

↓

to the understanding that innovation processes could be spurred both upstream and downstream with technology-push/demand-pull measures

↓

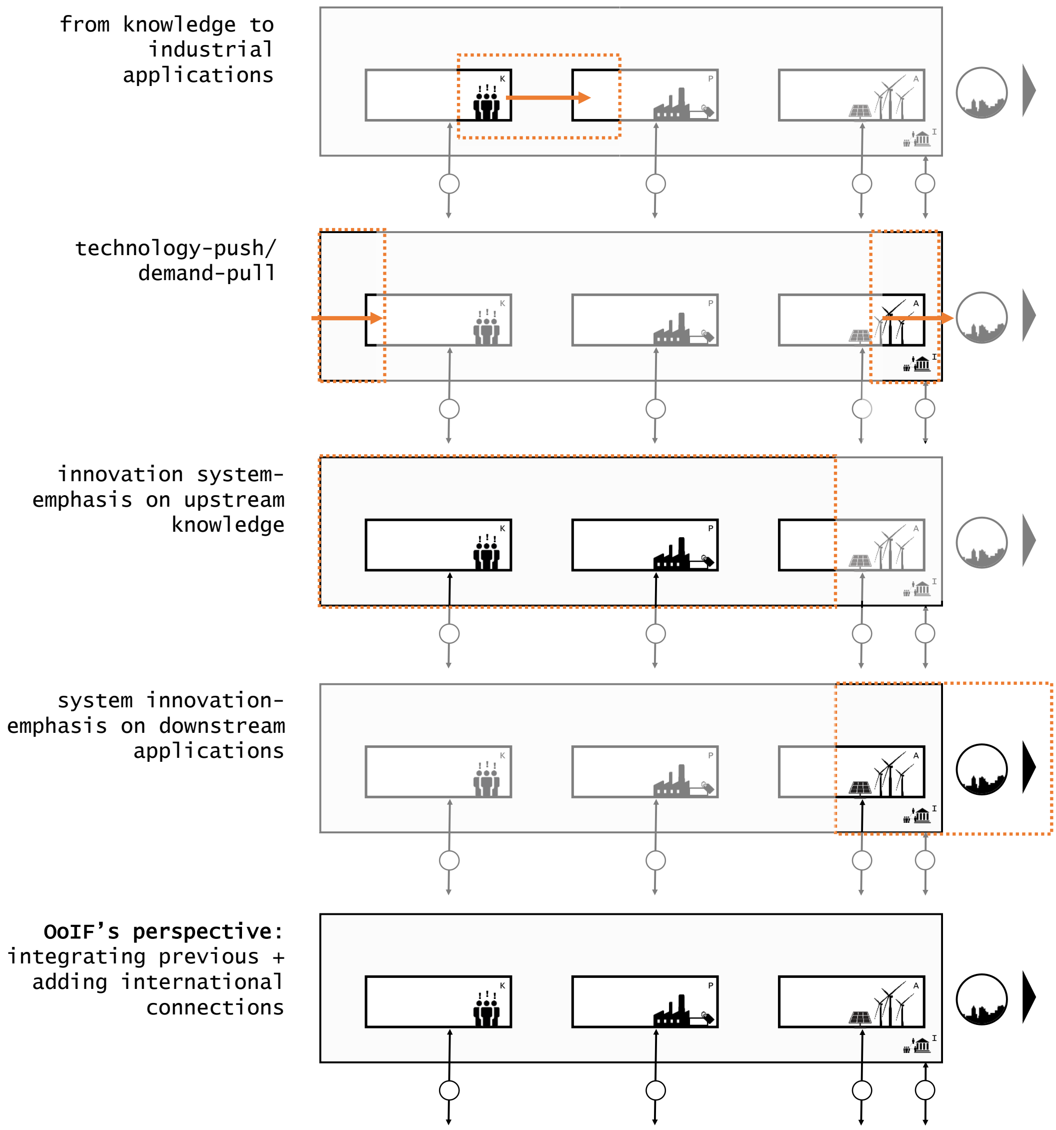
to the understanding that innovation processes are intertwined forming an innovation system -with particular emphasis on the upstream generation and exchange of knowledge

↓

to the understanding that technological innovation impacts the configuration of our socio-technical systems in ways that may or may not be sustainable -with particular emphasis on the downstream application of technologies.

Now, with OoIF, we aim to integrate these perspectives and to add an additional dimension in our understanding of innovation policy: the relevance of cross-national innovation dynamics and the potential to developing multilateral relationships. Figure 34 provides a visual illustration of these ideas.

Figure 34: Evolution in our interpretations of the focus of innovation policy



Source: Own elaboration

4.3. Consideration of policy mixes

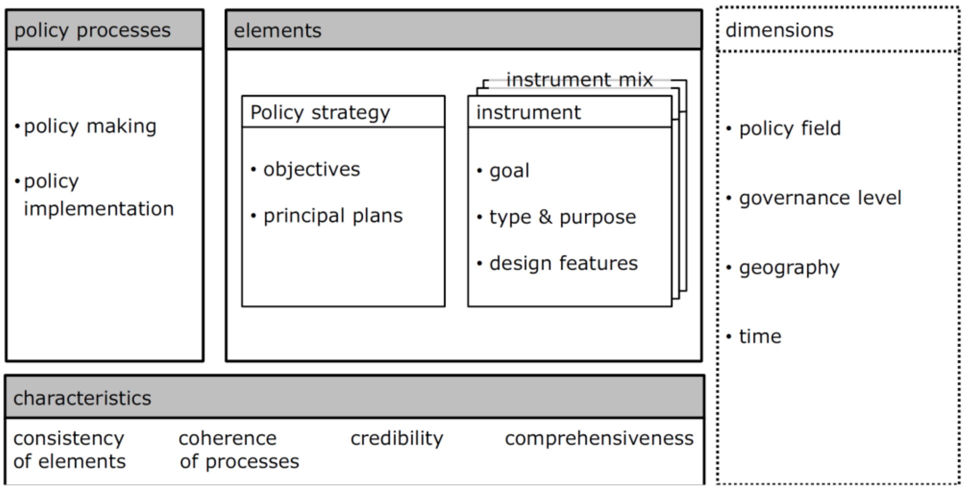
Another way in which we think OoIF can be useful in innovation policy-making is in supporting the mapping of innovation policy options.

Lately there has been a call in the literature to articulate (energy) innovation policy in terms of 'policy mixes' (del Río, 2014; Kivimaa and Kern, 2016). The underlying idea is that innovation, and energy innovation in particular, is affected by policy decisions taken from many different policy domains (R&D policy, industrial policy, energy policy…) and implemented through a wide variety of instruments (regulation, prices, incentives, etc.).

Thus, the interaction among policy domains and policy instruments may result in unexpected outcomes (Flanagan et al., 2011).

If instead of considering individual policies separately we could consider them as 'policy mixes', acknowledging their multi-dimensionality and complexity, we could aim for increased degrees of coordination, coherence, and comprehensiveness of policies (Rogge and Reichardt, 2016). Figure 35 provides a representation of some key elements that can be considered as building up policy mixes.

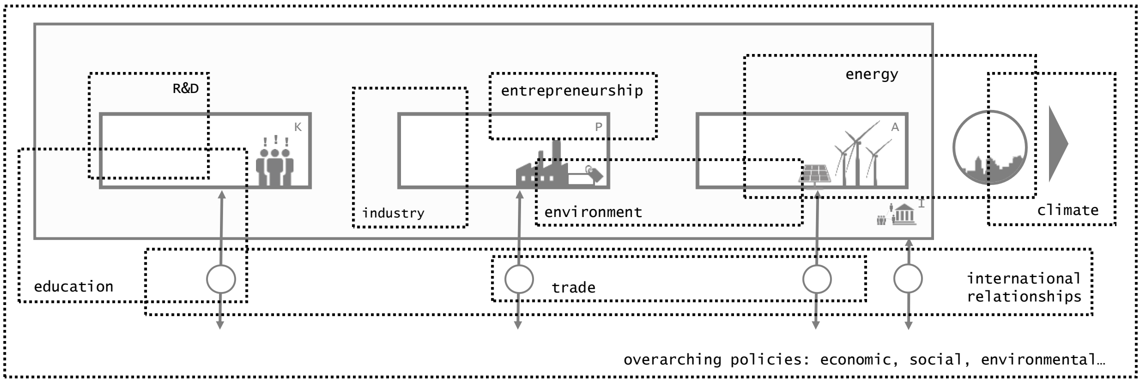
Figure 35: Building blocks of the extended policy mix concept



Source: (Rogge and Reichardt, 2016)

We think OoIF could help advance our understanding of innovation policy mixes at least in two ways: by helping to articulate and discuss policy goals more clearly, and by providing some basis to interpret the overlaps and complementarities among policy domains. In Figure 36 we sketch how different policy domains can be located on the OoIF framework as affecting its building blocks. This provides some visual illustration of how different policies may be complementing and overlapping to affect overall energy innovation.

Figure 36: Interpreting interrelated policy domains with OoIF



Source: Own elaboration

4.4. Multilateral relationships

Finally, we think OoIF may contribute to (energy) innovation policy-making by providing some basis to identify and categorize cross-country relationships. Table 14 offers a summary of the dynamics across innovation systems we have included in OoIF.

Table 14: Summary of dynamics across innovation systems (OoIF-dx)

↓ Dynamics across	Activities →				
Technology transfer	Vertical knowledge transfer	→	→		
	Vertical technology transfer		→	→	
	> absorptive capacity	⋯	⋯	⋯	
	> intellectual property rights	—□—	—□—		
	> technological characteristics		—□—	—□—	
Competition	e.g. for talent	↕−			
	e.g. in manufacturing cost		↕−		
	e.g. for physical & financial resources			↕−	
	e.g. confrontational trade policy				↕−
Collaboration	e.g. research partnerships	↕+			
	e.g. joint ventures		↕+		
	e.g. collective purchase			↕+	
	e.g. global governance efforts				↕+
Knowledge spillovers	e.g. labor mobility	↕s			
Value chain	e.g. design / production / installation		↕		
Social acceptance	e.g. investors' perceptions			↕ —	↕

Source: Own elaboration

In particular, we would like to encourage the use of OoIF to explore synergistic multilateral relationships that could contribute to the overall advancement of cleaner technologies while providing beneficial outcomes for countries. This is particularly relevant in a time when we are trying to advance international negotiations for climate change mitigation, and when -as discussed previously- weaving collaborative relationships represents one of the pillars of our global agenda for sustainable development.

Chapter 7_

Conclusions

The synthesis of a journey

Conclusions.
The synthesis of a journey.

In this thesis we have seen how energy innovation policy, even when designed at the national or regional level, needs to incorporate the global perspective. This emerges from the realization that innovation processes -at least for some renewable technologies such as wind and solar PV- have become increasingly globalized, and thus failing to respond to the unfolding global innovation dynamics or to engage proactively in them may well result in crashed expectations and missed opportunities. It also emerges from the realization that we need global scale efforts to tackle climate change, which urge us to find collective ways to make energy innovation work effectively towards a widespread low-carbon transition.

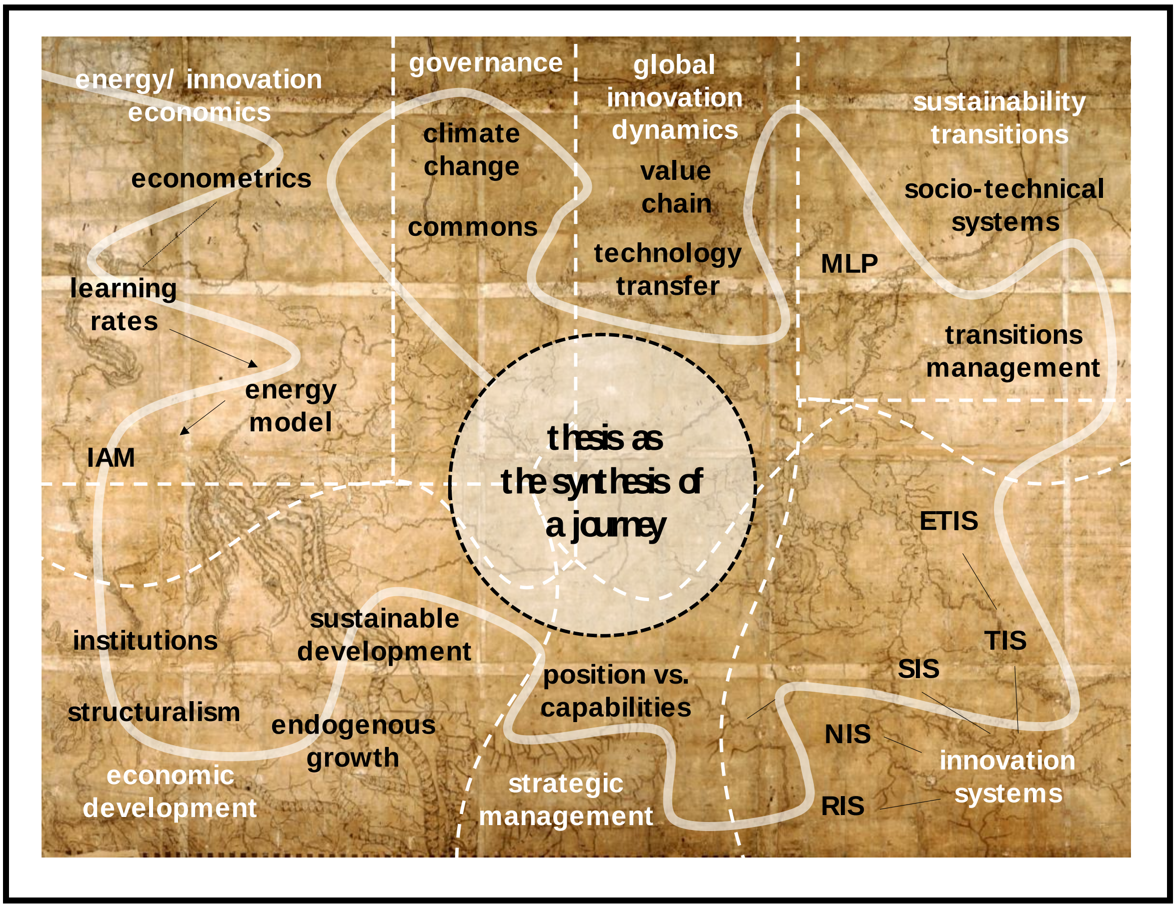
We proposed the Outcome-oriented Innovation Framework (OoIF) as a diagrammatic representation that helps in interpreting the global innovation system as interconnected countries' innovation systems, and in interpreting innovation outcomes through the lens of sustainability. We used OoIF to understand how the distribution across countries of innovation-related outcomes for wind and solar PV technologies has been highly dynamic, and how some international dynamics have been key in determining the shifts. From there, we discussed policy implications, both from the perspective of a country and for the global perspective in the context of climate change negotiations, and we described some specific ways in which OoIF could be used for innovation policy-making.

Overall, this document has presented a synthesis of the questions and answers I have found trying to understand how energy innovation policy could become more 'strategic' - interpreted as contributing to generating welfare for countries and alleviating global sustainability challenges.

Looking back, I appreciate it has been a journey across various disciplines and fields of study -see Box 11 for my attempt to depict the route taken.

Box 11: My exploration map: depicting the journey of this thesis as a route across disciplines and fields of study

Tracking back the journey...



In this final chapter, we summarize the research contributions and limitations of the thesis, in terms of conceptual contribution (Section 1), empirical evidence (Section 2), policy implications (Section 3) and policy applications (Section 4). We also suggest some lines for future research (Section 5).

1. Conceptual contribution

In this thesis we have provided a novel perspective on how energy innovation contributes to generate welfare through the lens of sustainability, as emerging from distinctive, complementary, and interconnected innovation-related activities. Building on this idea, we proposed the Outcome-oriented Innovation Framework (OoIF) as a framework specifically conceived to facilitate the interpretation of innovation outcomes.

OoIF is built around four activities: knowledge creation and exchange, technology production and commercialization, technology adoption and use, and institutional developments. We depicted the dynamics that hold these activities together within a country's innovation system (including knowledge, market and institutional dynamics), and also the dynamics that interlink them across countries.

We conceived OoIF as a ‘cut’ to the complex innovation reality complementary to other ‘cuts’ in the literature -one that is able to expose more clearly the distribution of outcomes across innovation activities and countries, while of course losing focus on other aspects other frameworks are more ready to reveal. Some of the aspects that OoIF reflects poorly are the following:

- Agency and power -represented only at a very aggregated level as institutional advancements vs institutional lock-in. Transition frameworks are much better equipped to reveal these.
- Structure and interactions -represented only partially and at a very aggregated level as knowledge ‘exchange’ and overall learning dynamics. Innovation systems frameworks allow to appreciate both the configuration of the system and the interactions within it at a much greater level of detail.
- Financial and material resource flows -not represented in OoIF, and yet relevant. Financial flows have been studied in the innovation economics literature; material flows are largely missing from current approaches. Indeed, we think that OoIF’s structure could provide a useful basis for the consideration of these flows. Exploring this could constitute a line for future developments of the framework.
- Technological and socio-technical characteristics -incorporated only as affecting the exportability of technologies. There is currently limited understanding of how technological and socio-technical characteristics influence innovation dynamics (Anadon et al., 2015). This could also be an avenue of future work.

On the other hand, we could summarize the conceptual contributions and relative strengths of OoIF in the following points:

- Built specifically to interpret the outcomes of technological innovation, 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.

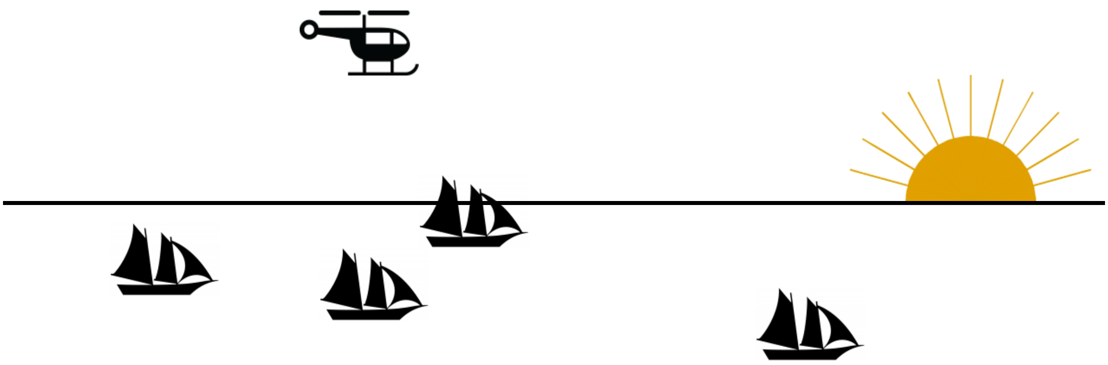
It is also worth-noticing that, while OoIF has been conceived and tried out for renewable energy innovation technologies, the concepts around which it is built have been largely studied in the literature for a wider spectrum of technologies. Therefore, we intuit OoIF could probably be useful for the study of other technological fields beyond renewables, although this proposition would need to be contrasted through empirical analysis in other applications of OoIF.

Box 12: Describing OoIF's perspective with the 'innovation as a sailing journey' metaphor

Seeing the scene from a helicopter

What if you could jump in a helicopter and see a sailing ship from above?

You could get a particular perspective of the ship -the silhouette of the vessel from above, the relative position of the sails…-, of the route it is tracing towards the horizon, and of how it relates to other ships in the scene.



This perspective from the helicopter could prove very useful to improve the journey, by considering all these aspects in an integrated way. However, we need not to forget that by jumping in the helicopter we will be missing out some very relevant aspects for navigation that can only be appreciated by putting our feet onboard.

2. Empirical evidence

This thesis has also contributed to provide empirical evidence on the globalization of innovation activities and the impact of transnational dynamics for the cases of wind and solar PV technologies.

First, we have offered a visual representation of how the distribution of innovation activities across countries in these technologies has evolved in the period 2000-2013. In particular, for eight countries particularly relevant in the development of these technologies -US, Germany, Denmark, Spain, Italy, China, Japan, and South Korea-, we depicted the evolution of some quantitative indicators (as a percentage of the world's total) -patents, exports, annual installed capacity, electricity generation, and CO_2 emissions- and discussed how these could be linked to the outcomes countries have been able to realize. Although the use of these indicators is not new in the literature[43], our study contributes by providing a novel way of representing and interpreting them, and also by analyzing both technologies -wind and solar PV- in parallel for a broader understanding of the evidence.

Second, we have gathered the evidence provided in the literature on the existence and relevance of transnational dynamics affecting innovation processes. In particular, we articulated the discussion around the cross-national innovation dynamics identified in OoIF -international competition/collaboration, knowledge spillovers and technology transfer, value chain relationships and trends in social acceptance- and evidenced how all have been relevant in the innovation stories of wind and solar PV, to the extent that we could suggest there is a 'global innovation system' for these technologies.

In short, the case of wind and solar PV in recent years illustrates how innovation in renewable technologies is happening at a global scale, how different countries are contributing to it in different ways and in turn being able to capture different outcomes, and how transnational dynamics have become very relevant.

3. Policy implications

Both the conceptual and the empirical discussion provided in this thesis have pointed to the importance for energy innovation policy to take into account the transnational

[43] Studies looking at similar indicators, but with different problem framing and representation, and only for the case of solar PV include (Zheng and Kammen, 2014) and (Binz et al., 2017). (Pegels and Lütkenhorst, 2014) also used similar indicators to analyze Germany's performance in wind and solar PV as compared to other leading countries.

dimension of innovation processes -something which is largely missing in current innovation frameworks and policy approaches. Therefore, another source of contributions of this thesis has been the discussion of the policy implications that appreciating the global scale of innovation processes in renewable technologies has.

We framed this discussion in the understanding of the potential tensions between countries' pursuit of (short-term) benefits and the need to overcome a severe and urgent global challenge as the one posed by climate change. From this perspective, our goal would be to make the global innovation system for clean technologies work as effectively as possible while articulating viable paths for countries. Then, the challenge for countries' energy innovation policy could be articulated as how countries could better design their policies affecting clean technologies in a way legitimately aligned with their national interests while contributing effectively and sufficiently to global efforts to mitigate climate change.

From the perspective of a country, we highlighted the following policy implications:

- The need for (neither fully deliberate nor fully emergent) strategic policy approaches that:
    - promote the development of those technologies and segments of the value chain where countries can better contribute to create value.
    - encourage proactive engagement in the global innovation system to take advantage of synergistic cross-country relationships.
- The need to advance our policy discourses and processes to favor the pursuit of sustainability. In particular, we suggested how we could:
    - broaden our interpretation of innovation policy and advance our narratives to recognize innovation impacts in the longer term and on the global scale.
    - cultivate well-grounded socio-political support for these technologies, through the building up of shared visions and the implementation of inclusive, transparent policy processes that are both adaptable and prone to learning.

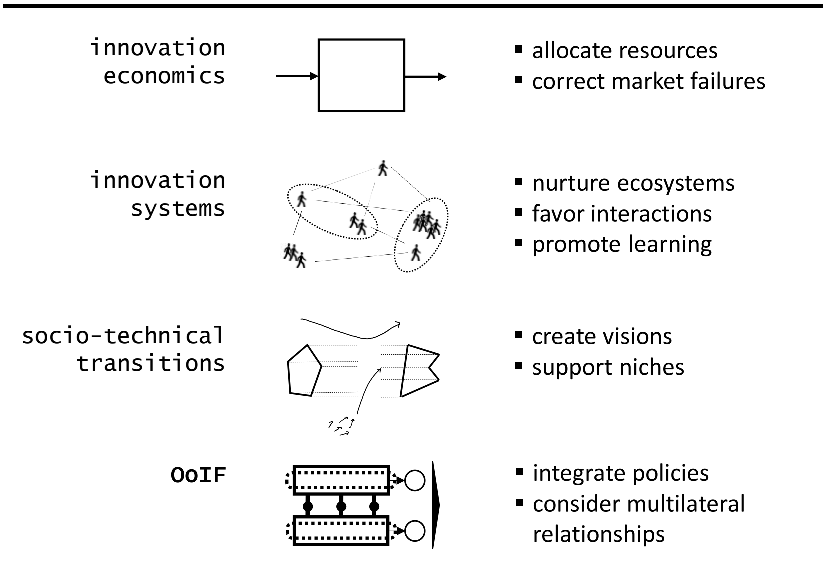
From the global perspective, we concluded that we should explore how to increase the effectiveness of our global innovation system by means of international collaboration. We identified four types of collaboration depending on the depth of transformation they involve: opportunist, committed, redistributive and structural. We suggested that we could regard the challenge of climate change as an opportunity to try out multilateral collaborative approaches in all these dimensions.

Collaborative relationships among countries could not only help us unleash the potential of technological innovation at a global scale, but also enable us to build the institutions that can get us better prepared to deal with global sustainability challenges in the future. This is indeed very much in line with the spirit of the recently approved 2030 Agenda for Sustainable Development.

4. Policy applications

We discussed how the way in which we depict innovation processes conditions the type of policies we can imagine and implement. We believe that, by offering a novel perspective and way of depicting innovation processes, OoIF can enable policy approaches that complement those offered by other frameworks. In Figure 37 we sum up the policy approaches that previous perspectives in the literature have suggested, and how OoIF adds to them by encouraging the integration of policies and the consideration of multilateral relationships.

Figure 37: Policy approaches encouraged by current innovation perspectives & how OoIF adds to them



Source: Own elaboration

We suggested four possible ways in which OoIF can be applied in innovation policy-making:

- To support strategic thinking
- To help integrate innovation policy approaches coherently

- To provide some basis for the understanding and configuration of policy mixes
- To identify and articulate cross-country relationships

Box 13: Final reflection on the purpose of innovation and how different innovation policy approaches -including that offered by OoIF- appear relevant, with the 'innovation as a sailing journey' metaphor

What matters for a truly enjoyable journey?

Have you realized you are in this ship too? We are all sailors, even if we often don't realize: as producers and 'exchangers' of knowledge, as workers that contribute to the production and commercialization of technologies, as consumers that determine to what extent technologies are adopted, as citizens that build collectively the institutions shaping technological development…

And have you realized that many before you have joined this ship and many others will join after you depart? Indeed, we mentioned in the introduction how the innovation journey is a continuous process: *"we never step on dry land, we are always sailing"*…

So this is probably about allowing *all* of us to enjoy the journey, and allowing those coming *after* us to enjoy it as well -arguably, at least as much as we did.

What matters then for a truly enjoyable journey in the short and long term? Some factors that will probably matter are:

- how uncertainties unfold -wind, currents, storms…
- what happens within the ship -how well we are able to interact, learn, improve our navigation skills…
- the direction taken -which determines our probabilities to enjoy sunny weather or a fatal storm…
- AND how we relate to other ships -by coordinating and collaborating we may well increase our chances to have an enjoyable ride!

5. Future work

Finally, we would like to point to three main lines for future research that could extend the contributions of this thesis.

FW1- Conceptual developments to OoIF

The first line of future work we would like to suggest is the conceptual refinement and potential reconfiguration of the Outcome-oriented Innovation Framework itself. While there are many ways in which we think OoIF could be improved and extended (we mentioned them when pointing out its limitations), there are three that we consider particularly relevant to improve our understanding of how innovation policy can contribute to advancing sustainability:

a. *Incorporate the consideration of distributional aspects*

In OoIF, we assumed that innovation activities may lead to positive variations in capitals at the aggregated level, that would in turn allow for increased overall wellbeing, but did not explore the intricacies of how innovation outcomes get distributed among governments, companies and people, or particular subgroups of them, which would nevertheless be crucial to understand to what extent and for whom innovation activities translate (or not) into improvements in wellbeing. 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.

b. *Explore the connections between the innovation system and the ecological system*

OoIF, as other frameworks in the innovation literature, has treated the ecological system as exogenous to the innovation system. However, given the large environmental implications that technology may have (both positive and negative), we believe considering explicitly the interconnections between the innovation system and the ecological system could facilitate the conception of innovation policy that really allows us to overcome environmental challenges -rather than, perhaps unintentionally, creating new ones.

c. *Explore circular approaches for generating value*

In connection to the previous point, we suggest that it could be interesting to explore how a circular approach could be ingrained in the framework, beyond the current limited representation as a circle that connects production and consumption activities. We need to improve our understanding of how innovation policy could favor the generation of circular value beyond the traditional linear scheme of value generation through technology production > distribution > installation > use.

FW2- Deepening and broadening the empirical analysis

A second avenue for future work would be the deepening and broadening of the empirical analysis provided in this thesis.

On the one hand, we could go deeper in the cases of wind and solar PV technologies. For instance, we could focus in a particular country and apply fully the OoIF framework to analyze also internal dynamics (the cases in this thesis focused on the analysis of outcomes and international dynamics), and reflect on innovation processes in that country with greater level of detail.

On the other hand, we could develop case studies for other technologies, both in the energy domain and in other domains, to test the usefulness of OoIF in different contexts. It will be particularly interesting to analyze to what extent OoIF could be used when considering digital, disembodied innovations.

FW3- Exploring further the means and potential of multilateral collaboration

Finally, we believe there is much room for improving our understanding of the means and potential of multilateral collaboration for dealing collectively with global sustainability challenges. We have suggested how we need “penguin solutions” -solutions in which doing the best for the world is best for countries too- to deal with problems such as climate change. Yet, we argue that we still have a long way to walk in imagining, designing and implementing these “penguin solutions”.

Indeed, it is only very recently in history that we have become aware of the global dimension of development, so we are still in the process of building up the institutions that may help us to deal adequately with this dimension. Exploring “penguins solutions” for energy innovation, deepening in our understanding of international dynamics and means for collaboration -perhaps building on strands of literature such as game theory and the governance of the commons- would probably be the most relevant line of work to advancing the contributions of this thesis.

Annex_

A personal account on interdisciplinarity

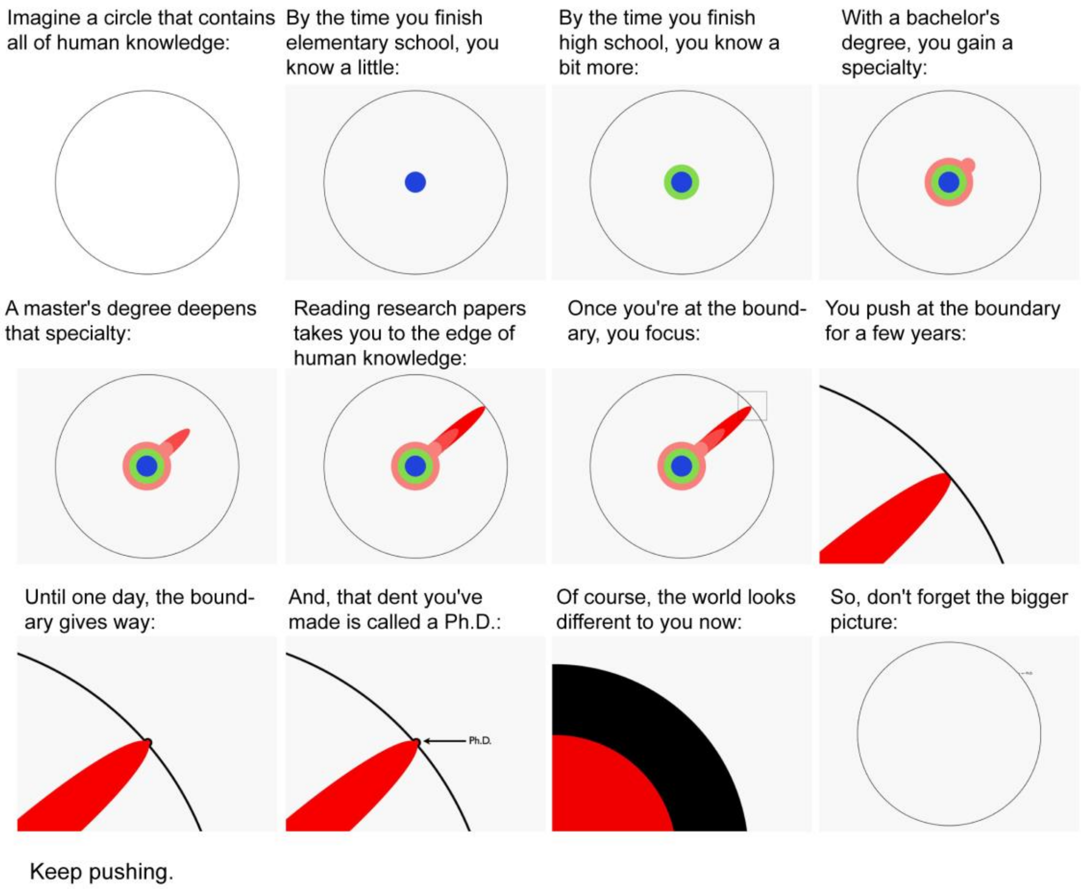
A personal account on interdisciplinarity

In this Annex, I would like to share a personal account on what interdisciplinarity has meant in the process of this PhD thesis, hoping the perspective offered might be useful for others going into the muddy yet -I believe- rewarding journey of interdisciplinarity.

1. Is it really always about pushing?

At some point, short after I began my PhD, I stumbled upon the idea that doing a PhD is contributing to expanding existing knowledge by pushing at the ‘knowledge frontier’. I even found out a visual illustration of the idea that seemed very appealing -see Figure 38.

Figure 38: “The illustrated guide to a PhD”, by Matt Might

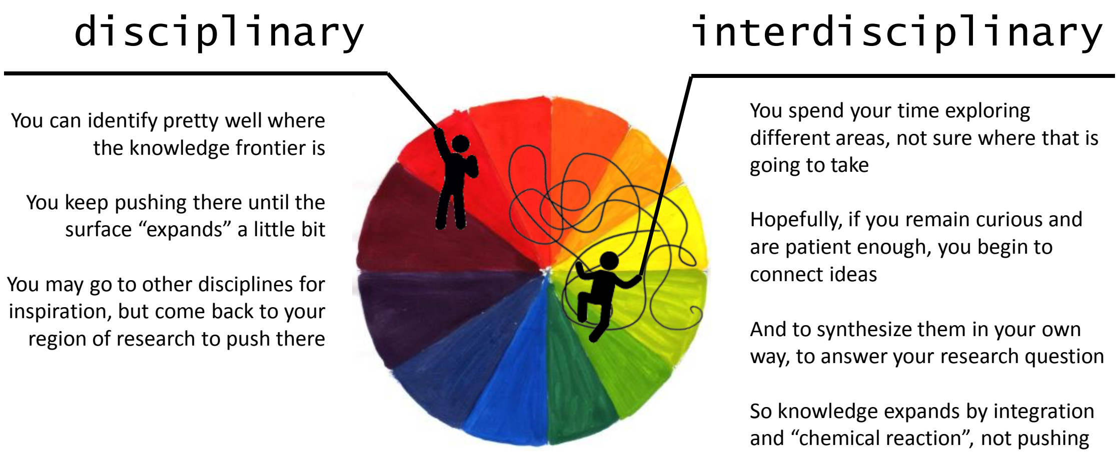


Source: http://matt.might.net/articles/phd-school-in-pictures/

I was therefore expecting to identify clearly and early in the process my place in the knowledge frontier, then pushing there for some years, until that frontier gave away. However, things turned out to look very differently... I have not been sure where my point for contributing was until the very last stage of the PhD. I have been wandering around different disciplines and fields of study, driven by a very open question, feeling 'lost in space' instead of pushing at a certain point. And I felt I was doing wrong, that I had to hurry up to find that point and begin pushing -otherwise the thesis would never be realized.

However, with the perspective that only time gives, and now that I have managed to give shape to this document, I think I just underwent a different kind of process to the one that Matt Might illustrated. And I intuit that perhaps that process was needed for the type of question I had, one that could not be answered from a single discipline or field of study. Perhaps, disciplinary research and interdisciplinary research require different types of processes, and different attitudes by the researcher -see Figure 39 for a representation of my personal interpretation on this.

Figure 39: My interpretation of how disciplinary and interdisciplinary research processes differ



Source: Own elaboration

2. A role for 'design thinking' in academic research?

Unexpectedly, the discovery of 'design thinking' has helped me undergone this uncertain process. It is not my purpose to describe design thinking in detail here, I only summarize how it compares to analytical thinking in Table 15, and highlight next some ways in which it has been helpful for my research process -even if at first sight design thinking seemed to have little connection with academic research. Ultimately, what I try to propose is that, even if academic research requires high doses of analytical thinking, combining it with some design thinking can be very helpful to undergone interdisciplinary research aiming to respond to broad questions or messy problems.

Table 15: Comparison between analytical thinking and design thinking

analytical thinking	design thinking
data driven	people driven
individualist	collaborative
objective	optimist
neutral	experimental
lineal	iterative
guided by problem	guided by solution
defining parameters, identifying constraints…	searching for assumptions, drivers, alternatives…
consideration of constraints	no limits during brainstorming (defer judgement)
convergent thinking	divergent thinking
rationality	creativity

Source: Own elaboration

Design thinking emphasizes the need to 'live the question'. As expressed by Barry MacDevitt, from Design Dublin, *"we all have a tendency to jump to solution mode far too quickly… Design thinking approach forces you really to live in this unclear, sometimes very muddy place to get a better understanding. This ends up producing a much better understanding of the problem and the challenge that you are trying to solve"*. At least from my experience, I believe this is very applicable to interdisciplinary research: by accepting the confusion and messiness of exploring different fields, you may be well building the grounds for a much deeper understanding.

Some have compared the role of the designer to that of a museum curator -see Box 14 for a description of what a museum curator does. Could not that be interpreted also as the role of an academic researcher? As museum curators, academic researchers need to survey what is out there and identify the most relevant works connected to their research question, making a judgement of what matters and what doesn't. This is probably equally true for both disciplinary and interdisciplinary research. However, I believe the final two points in Box 14 are much more relevant to interdisciplinary research than they are to disciplinary research: the need to "*drill down to the essence by assembling some combination of the most revealing*" and the need to "*tell the story in a way that is compelling and educational*".

Box 14: The role of a museum curator

What does a museum curator do?

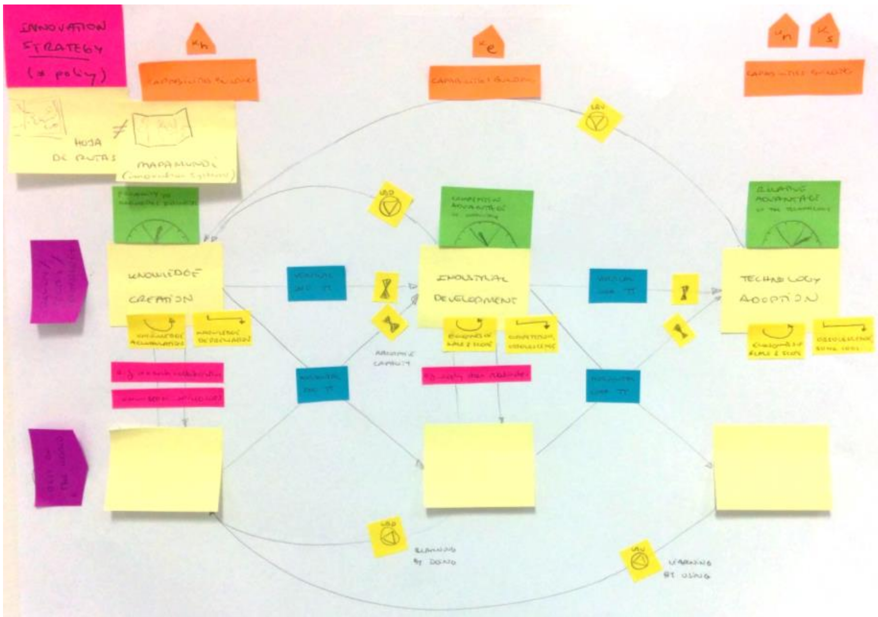
- Surveys what is out there and makes sure all important works are identified
- Makes a judgment as to what matters and what doesn't
- Drills down to the essence by assembling some combination of the most revealing
- Tells the story in a way that is compelling and educational

Source: 'Design thinking for innovation' course at Coursera, led by Jeanne M. Liedtka, from the University of Virginia

Design thinking has helped me approach the research as an iterative process, in which you need to prototype and constantly revise your initial assumptions (a key trait of methodologies based on design thinking). A way in which I applied the idea of prototyping in the context of this thesis has been using post-its to build panels of ideas. The use of post-its allowed me to quickly rephrase, reconsider or discard ideas, and to organize them visually. Figure 40 provides an example of one of the many panels of ideas developed during this thesis, and Figure 41 a picture of the initial prototype of the model that led to the OoIF framework.

Figure 40: Example of panel of ideas with post-its

Figure 41: Initial prototype of the model leading to the OoIF framework



Finally, design thinking tends to be very visual, and encourages you to express ideas through sketches, diagrams, images… Couldn't academic research and writing benefit from expressing ideas more visually? In this thesis I made my attempt to use figures and metaphors to communicate and illustrate complex ideas, hoping they could facilitate understanding -and perhaps, who knows, inspire others to express their ideas more visually too.

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