Groupe de Recherche en
Économie Théorique et Appliquée

Mapping technological knowledge patterns: evidence from ocean energy technologies

Maïder SAINT-JEAN
GREThA, CNRS, UMR 5113, Université de Bordeaux
maider.saint-jean@u-bordeaux.fr

Nabila ARFAOUI
ESDES, Université Catholique de Lyon
narfaoui@univ-catholyon.fr

Eric BROUILLAT
GREThA, CNRS, UMR 5113, Université de Bordeaux
eric.brouillat@u-bordeaux.fr

David VIRAPIN
GREThA, CNRS, UMR 5113, Université de Bordeaux
david.virapin@u-bordeaux.fr

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GRETHA UMR CNRS 5113
Université de Bordeaux
Avenue Léon Duguit - 33608 PESSAC - FRANCE
Tel : +33 (0)5.56.84.25.75 - Fax : +33 (0)5.56.84.86.47 - www.gretha.fr

Cartographie des connaissances technologiques : le cas des énergies marines renouvelables

Résumé

Nous étudions la structuration des connaissances qui sous-tendent l'évolution des trajectoires technologiques des énergies marines renouvelables (EMR), à savoir l'énergie marémotrice, houlomotrice, l'énergie thermique des océans, l'énergie osmotique et l'éolien offshore. L'examen des relations liant les éléments constitutifs de la base de connaissance relative aux EMR, en particulier leur degré de substituabilité et de complémentarité, permet de mieux apprécier la cohérence de cette base de connaissances ainsi que des trajectoires technologiques au sein du secteur. Pour ce faire, nous nous appuyons sur des données de brevets extraites de la base de données Questel ORBIT. A partir des codes de la classification coopérative des brevets (CPC), nous identifions les différentes options techniques liées aux EMR et extrayons un ensemble de brevets octroyés entre 2000 et 2015. Nous analysons les principales tendances issues des statistiques sur les brevets et construisons un réseau de citations auquel nous appliquons l'algorithme *main path* afin de cartographier tous les sentiers d'accumulation de connaissances technologiques envisageables et d'identifier les plus importants d'entre eux. Nous montrons que le socle de connaissances et les trajectoires technologiques associées aux EMR sont divisés en deux grands ensembles, selon que les connaissances nécessaires à l'exploitation et la conversion en électricité de l'énergie des océans proviennent des sciences physiques ou bien de la chimie. Les trajectoires des différentes EMR apparaissent alors compartimentées, avec peu de connexions entre elles. Toutefois, des liens entre les énergies marémotrice, houlomotrice et l'éolien offshore s'établissent autour de brevets pivots, fondements de la base de connaissances des EMR. En nous concentrant spécifiquement sur la famille des EMR reposant sur les sciences physiques, nous étudions les aspects structurels de cette base de connaissances et analysons le niveau global de complémentarité et de substituabilité de ses éléments constitutifs. Notre analyse confirme en partie l'accroissement au cours du temps de la cohérence de la base de connaissances, mais met également en évidence son caractère fluctuant qui, d'une certaine manière, reflète la nature intermittente du financement de l'énergie issu des océans, ce qui retarde le consensus autour des architectures et designs, clés de la commercialisation de ces technologies.

Mots-clés: énergies marines renouvelables, réseaux de citations, base de connaissance, complémentarité, substituabilité, design dominant

Mapping technological knowledge patterns: evidence from ocean energy technologies

Abstract

This article investigates the technological knowledge pattern underlying the recent evolution in ocean energy technology (OET) trajectories, especially tidal and wave energy, ocean thermal energy, salinity gradient energy and offshore wind energy. Examination of the relational properties among the knowledge elements in the OET knowledge base, in particular, their substitutability and complementarity, allows a better understanding of the coherence of this knowledge base and the technological trajectories within the sector. We use patent data extracted from the Questel ORBIT database. The various technical options related to OETs are identified by Cooperative Patent Classification (CPC) codes and enable the construction of a dataset of OET patents granted between 2000 and 2015. We analyze the main trends emerging from the patent statistics and we construct a network of citations among OET patents and apply to it a main path algorithm. This allows a mapping of all possible streams of cumulative growth of technological knowledge and identification of the most important ones. We show that the knowledge base of OETs is split into two main families and technology patterns depending on whether the harnessing of ocean power and its conversion to renewable low-carbon electricity derive from physical or chemical science. OET trajectories are somewhat compartmentalized with few connections amongst them; however, there are links between some pivotal tidal and wave energy and offshore wind energy patents which have become the foundations to an OET knowledge base. By focusing specifically on the physics-based family of OETs, we can investigate the structural aspects of this knowledge base and analyze the aggregate level of complementarity and substitutability of its knowledge constituent. Our analysis partly confirms the increased coherence of the OET knowledge base over time but also highlights its fluctuating nature which in some ways mirrors the intermittent nature of ocean energy funding, further slowing consensus over designs which is key to commercialization.

Keywords: Ocean energy technology, citation network analysis, knowledge base, complementarity, substitutability, dominant design

JEL: codes JEL : O33, Q42, Q55

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GRETHA UMR CNRS 5113
Université de Bordeaux
Avenue Léon Duguit - 33608 PESSAC - FRANCE
Tel : +33 (0)5.56.84.25.75 - Fax : +33 (0)5.56.84.86.47 - www.gretha.fr

1. Introduction

At present renewable energy sources such as solar, wind, geothermal, marine, hydropower, waste and biomass energy, represent only 19.2% of global final energy consumption compared to 78.3% for fossil-fuels and 2.5% for nuclear energy (REN21, 2016). Increasing the share of electricity produced from renewable sources could greatly reduce levels of greenhouse gas emissions from the power generation sector which currently is responsible for some 30% of carbon emissions in Europe. In recent years, a strong political ambition to develop ocean energy technologies (OETs) has emerged especially in Europe, aimed at making OETs an integral part of future energy production (SI Ocean, 2014). In January 2014 the European Commission launched the Blue Energy Communication (European Commission, 2014) to highlight the expected contribution in Europe of ocean energy [1] and to set a framework for the development and diffusion of the OETs by 2020 and beyond[2]. Magagna and Uihlein (2015) emphasize that OETs face four main bottlenecks: technology development, finance and markets, environmental and administrative issues, and grid availability. Currently, technological issues are the main barrier which OET developers need to address in the short–medium term (MacGillivray et al., 2013). However, there is little quantitative evidence on the innovation dynamics related to these technologies. MacGillivary et al. (2015) point out that their scarce physical deployment means that research into the technological dynamics of OETs is restricted mostly to theoretical analyses and assumptions about future trajectories.

This paper contributes to filling that gap by mapping the technological knowledge underlying the long-term evolution of OET trajectories. Technological trajectories can be seen as resulting from the (re)combination of the knowledge elements constituting a knowledge base (Nelson and Winter, 1982). In that sense, the relational properties of these knowledge elements can affect the search process. The pieces of knowledge constituting the knowledge base are more or less substitutable and complementary which may affect the coherence of the knowledge base, and in turn, the technological trajectories within the sector (Nesta and Saviotti, 2005; Dibiaggio et al., 2014). OETs are

[1] At present, OETs represent only a very small share of the global energy mix. At the end of 2015, global ocean energy capacity was approximately 530 megawatts (MW), against 227 gigawatts (GW) for solar photovoltaics and 433 GW for wind power (REN21, 2016). Yet OETs have vast theoretical potential; between 20 000 terawatt-hours (TWh) and 80 000 TWh of electricity per year, enough to satisfy between 100% and 400% of current global demand for electricity (IEA, 2013).

[2] The communication establishes a two-phase implementation plan. The first action phase (2014-2016) consists of creating an Ocean Energy Forum as a platform to bring together stakeholders and develop a shared understanding of the problems at stake, and collectively to devise workable solutions for the sector. The Ocean Energy Forum is expected to feed into the development of a strategic roadmap defining targets for OET developments on an industrial scale, and a clear timeframe for their implementation. The second action phase (2017-2020) involves creation of a European Industrial Initiative (EII) for Ocean Energy similar to that already in place for other renewables (e.g. the European Wind Initiative). A EII is a public-private partnership bringing together industry, researchers, Member States and the Commission to formulate and achieve clear common objectives within a specific timeframe. Its main objective is to enhance the effectiveness of innovative R&D and provide a platform for sharing the investment risks.

part of the technology competition characterising the transition in the energy sector from a fossil to a renewables based electricity system. They share a common knowledge base combining knowledge of the kinetic, chemical and thermal properties of seawater with knowledge about electricity production, but each technology presents variation in terms of combinatorial solutions as illustrated by the different technical characteristics of solutions for using the ocean to produce electricity.

In this paper, we investigate the structure of the knowledge base and the evolution of OET trajectories using patent data extracted from the ORBIT database. The various technological options related to ocean energy are identifiable by CPC codes which allow the construction of a dataset of OET patents granted between 1900 and 2015. We analyze the main trends emerging from the patent statistics which highlight how OETs have evolved over time depending on the relevant organizations and across different countries. We construct a network of citations among OETs patents and apply to it a main path algorithm which enables the mapping of all possible sources of cumulative growth of technological knowledge and identifies the most important stream. We use CPC technological classes to measure the relational properties of the knowledge base and examine the aggregate level of complementarity and substitutability of its constituent knowledge elements.

The article is organized as follows. Section 2 provides an overview of OETs and presents the analytical framework. Section 3 describes data set and methodology used, and section 4 presents the results of the patent analysis. Section 5 discusses the results and concludes the paper.

2. Overview of technologies and analytical framework

2.1. Technology competition during sustainability transition periods

Sustainability transition refers to the transformation of existing socio-technical systems (or regimes, including technologies, infrastructures, institutions, industrial sectors, user behaviors) towards environmental sustainability (Geels, 2002; Geels and Schot, 2007; Geels, 2016 et al.). Transition in the energy sector refers to a shift from a fossil to a renewables based electricity system. As Hofman and Elzen (2010) point out, the emerging new renewable technologies must both adapt to the existing regime and also transform or replace it. In this context, there is an old-*versus*-new competition between conventional technologies and cleaner technologies to satisfy similar functions (e.g. energy supply). In this perspective, the dominance of the established technology may impede deployment of the new technology; at the same time the new technology may be inferior in relation to the functions it is supposed to fulfil, and thus may be an imperfect substitute for the established technology.

In addition, there may be a simultaneous new-*versus*-new competition. Zundel et al. (2005, p. 22) suggest that: "since the solution of an environmental problem defines a new function, several technologies executing this function happen to compete with each other on the level new-*versus*-new as soon as this function is established by the corresponding demand (for example, by means of the corresponding regulation)." It has been shown that both types of competition occur in parallel and need to be considered together in order to understand the mutual interaction between the new technologies and their established counterparts (old technology investment cycle comparted to the new technologies' life cycles) on the one hand, and the critical momentum typically characterizing the competition among various new alternatives (importance of early stages, small events and increasing returns to adoption) on the other hand (Zundel et al., 2005).

During the technological transition phase when competing technologies emerge, explorative invention and experimentation are important to test different options related to problem solving. In the technology life cycle and dominant design literature (Abernathy and Utterback, 1978; Abernathy and Clark, 1985; Murmann and Tushman, 2002; Murmann and Frenken, 2006; Lee and Berente, 2013), this corresponds to the '*era of ferment*' which culminates in a dominant design as the technology's core components become standardized. This is followed by an '*era of incremental change*' during which innovative activity is focused on process innovations and specialized materials as firms begin to sell into the mass market and compete primarily on cost until a new discontinuity triggers a new design competition (Abernathy and Utterback, 1978). However, in the case of complex products and systems characterized by core and periphery elements, the product-process shifts described by Abernathy and Utterback (1978) no longer hold. The pattern becomes more one of a shift from system architecture innovation to waves of innovations in sub-systems and components[3] (Davies and Hobday, 2005).

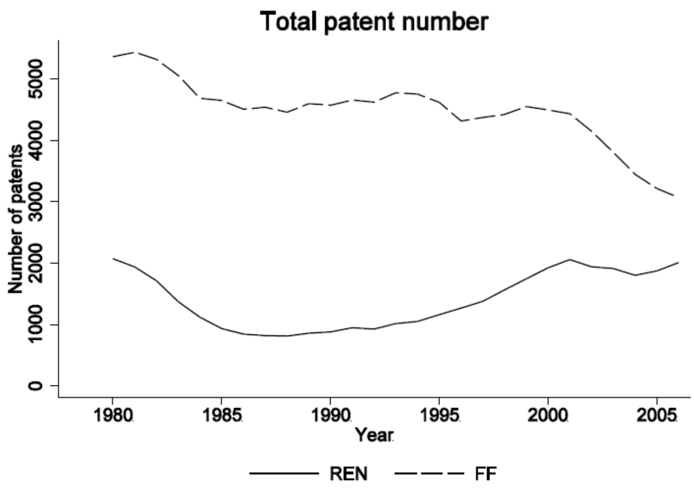
In the energy sector, Huenteler et al. (2016b) emphasize two main technological determinants of life-cycle patterns: the complexity of the product architecture and the scale of the production process. The complexity of the product is understood as based on the number of sub-systems and components and the complexity of their interactions in the system. The scale of the production process is driven mainly by the modularity of the system and the size and homogeneity of user demands. For example, Huenteler et al. show that wind turbine technology closely resembles the

[3] The early phase is characterized by a focus on functional performance and product innovations when competition is focused not on specific designs but on alternative product architectures. After the emergence of a dominant design (constituted by a common product architecture and standardized core sub-systems), innovation along the technological trajectory is focused on individual sub-systems and components (Murmann and Frenken, 2006).

complex products and systems life-cycle: over time the focus of innovative activity shifts to different parts of the product rather than from products to processes.

2.2. Ocean energy technologies

OETs are involved in both old-*versus*-new and new-*versus*-new competition. At the old-*versus*-new level, fossil fuel based technologies which are the established technology benefit from strong competitive advantage and a high level of maturity compared to renewable energy based technologies. The evolution of patenting activity reflects the latter's huge dominance. Noailly and Shestalova (2013) show that while the number of fossil fuel patents is largely higher than the number of renewable energy patents, in recent years, the latter have been catching up as the number fossil-fuel energy patents has declined over time (figure 1). Nevertheless, annual patent numbers for renewable technologies are still substantially below those for fossil-fuel technologies.



Note: FF – fossil fuel; REN – renewable energy.

Figure 1: The evolution of patent activities (total patent number for REN and FF technologies)

Source: Noailly and Shestalova, 2013, p. 8.

It is possible to distinguish three generations of renewable energy technologies according to the International Energy Agency (2008). (1) First-generation technologies which have reached maturity such as hydropower, biomass combustion, and geothermal energy; (2) Second-generation technologies which are undergoing rapid development such as solar energy, wind power, and modern forms of bio-energy; and (3) Third-generation technologies which presently are in the developmental stage such as solar power, ocean energy, improved geothermal, and integrated bio-energy systems. Figure 2 (from Johnstone et al., 2012), shows the total number of patent applications to the European Patent Office (EPO) for five renewable energy sources (solar, wind, ocean, geothermal, and biomass and waste).

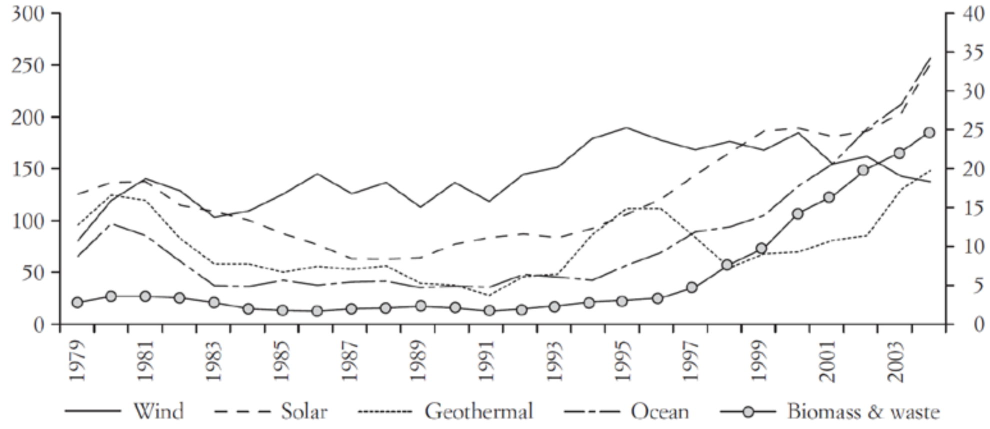


Figure 2: Number of EPO patent applications for renewables by type of technology (3-year moving average). Note: geothermal, ocean, and biomass & waste are shown on the right axis

Source: Johnstone et al. (2012), p. 140.

As expected, wind and solar power (left axis) have the highest counts. Solar power counts exhibit a U-shaped path, with growth since the early 1990s, and particularly since the turn of the 21st century. In the case of wind power, growth rates have increased markedly since the late 1990s. This increase in wind patents from the end of the 1990s is in line with the rise in installed capacity of wind turbines, supported by government programs promoting wind energy (e.g. in Denmark, the UK and Germany[4]). In addition ocean energy patenting has increased recently but from a very low base. In the case of geothermal and biomass/waste-to-energy there has been little growth in innovation levels since the 1970s.

At the new-*versus*-new level, different technology groups at different development stages coexist[5]. The evolution of patenting activity indicates significant variety in the number of alternative options, and an imbalance in patenting activity with major efforts in solar and wind but much lower patenting activity in the case of other technologies. However, although it is from a very low base the recent high growth in ocean energy patenting is worthy of attention. OETs is an emergent sub-group in the domain of renewable technologies. Even if OETs are based on the same resource (ocean) and have a

[4] See Klaassen et al. (2005).

[5] According to IRENA (2014), marine energy technologies include production of biofuels from marine biomass, energy from submarine vents, offshore wind (fixed or floating), floating photovoltaic technology and OETs. In the following analysis, we focus on offshore wind and OETs since the production of biofuels from marine biomass is more commonly considered a form of bioenergy rather than ocean energy, and the harnessing of energy from submarine vents is generally considered a form of geothermal energy. We also exclude floating photovoltaic technology since the main resource is the sun and not oceans.

common purpose (to produce electricity from renewable energy sources), this sub-group exhibits internal variety. Different sub-technologies are developed with different technological and commercial maturity. Those OETs are at an early stage in their technology life-cycle and in a continuing '*era of ferment*'. Thus, the emergence of a dominant design understood as a standard for the design of the technology's core components (Murmann and Frenken, 2006) is an important aspect conditioning successful commercialization of those technologies. Some OETs are relatively old and have regained relevance with the adoption of energy and climate policies. The possibility of obtaining energy from the oceans has inspired numerous inventors over the course of more than two centuries. According to Ross (1995) the earliest patent was filed by a Frenchman, Girard, in 1799. However it was not until the 1970s oil crisis that the international scientific community became interested in the ocean energy[6]. At that time, a number of countries introduced support for R&D in this area, followed by investment incentives (third-party financing, investment guarantees), and tax (exemptions, rebates) and price-support (tariffs, guaranteed prices) policies. More recently, several countries have imposed quantity certifications which are tradable among generators (IEA, 2009). Nowadays ocean energy is characterized by different technologies. A review of the specialized literature on OETs (Pelc and Fujita, 2002; Cruz, 2008; Falcão, 2010; IRENA, 2014; Osorio et al., 2016) allows us to distinguish four kinds of technologies[7]: salinity gradient, ocean thermal energy conversion (OTEC), ocean surface wave energy, and tidal energy. These technologies differ in both their technical characteristics and technology maturity (IRENA, 2014)[8].

Salinity gradient technology seeks to harness the chemical potential between freshwater and seawater captured as pressure across a semi-permeable membrane. It was invented many decades ago but is the least developed OET. As the salinity gradient resource is continuous, this technology is characterized by important potential to generate baseload power. However, very few technology developers[9] are interested in this technology and most studies are at an early R&D stage.

OTEC produces energy from the ocean's natural thermal gradient using the heat stored in its warm surface water to create steam to drive a turbine while pumping cold deep water to the surface to recondense the steam. Although OTEC is considered as having the highest theoretical global total

[6] Falcão (2010) shows that a 1974 paper by Stephen Salter published in the prestigious journal *Nature*, became a landmark study and brought wave energy to the attention of the international scientific community.

[7] Although they are an OET we do not consider technologies related to deep ocean currents which generate baseload power from ocean currents which are driven by latitudinal distributions of winds and thermohaline ocean circulation. This type of technology is similar to tidal current technology but is slower, continuous, and unidirectional. Moreover the large volumes of water and large scale of oceanic currents increases the potential compared to tidal current technology. However, although some developers are working on concepts developed by various universities and companies this technology remains at the laboratory scale.

[8] See Appendix A1.

[9] One small 4 kW pilot plant was opened by Statkraft in Norway in 2009 (IRENA, 2014).

resource potential among the various ocean energy resources, the energy density of OTEC systems remains quite low, leading the costs of electricity generation from OTEC to remain substantially higher than fossil fuel costs. Currently, OTEC can be considered at the laboratory stage.

Wave energy technology transforms energy from the kinetic and potential energy of ocean surface waves into electricity. Ocean surface wave formation essentially is influenced by the speed, duration and fetch (distance of open water over which the wind blows) of the wind. Wave energy has long been considered one of the most promising renewable technologies because the resource is vast and more available than most renewable energy resources[10] (Pelc and Fujita, 2002; Falnes, 2007; Falcão, 2010). Wave energy conversion has received serious academic attention since the early 1970s but extraction of wave energy at useful scales and reasonable cost has proven challenging, and full-scale prototypes have been developed only recently. Currently, there are several grid-connected pre-commercial prototypes which have been targeted for build-out into utility-scale arrays over the next 10 years.

There are two general approaches to tidal energy conversion: tidal stream, and tidal range. Tidal stream produces electricity by capturing the kinetic energy from the horizontal flow of tidal currents while tidal range captures the energy created by the difference in sea levels between high and low tides. Compared to some other sources of renewable energy, tidal power is regular and predictable which makes tidal technology an attractive resource option. At present, tidal technology can be considered the most mature OET. Tidal range is the only technology that has proven its technical viability and reliability in existing commercial projects. The tidal stream technology is less mature, and can be compared to the early stages of wind energy a few decades ago. Tidal stream technologies are at the testing and prototyping stage but large original equipment manufacturers (e.g. Alstom, DCNS, Hyundai Heavy Industries, Kawasaki Heavy Industries, Lockheed Martin, Siemens) are becoming increasingly interested in them.

Following discussions with experts[11], in addition to the four OETs identified above, we decided to include offshore wind turbines in the marine environment to our study[12]. The main reason for this choice is the two-way interaction between wind and ocean waves (Janssen, 2014): winds generate ocean waves but at the same time, winds are impacted by the state of the waves due to loss of energy and wave momentum. Therefore, it can be difficult to disentangle the power sources in

[10] Wave power is available up to 90% of the time compared to 20%–30% for solar and wind power.
[11] Poster presentation at the Seanergy Biarritz conference, 1-2 June 2016.
[12] A wind turbine is a device that converts the wind's kinetic energy into electrical energy. Offshore wind energy refers to wind farms constructed usually in the ocean to harvest wind energy to generate electricity.

relation to wind-driven waves[13]. Offshore wind is much more advanced than the four OETs. From the first commercial-scale offshore wind plant commissioned in Denmark in 2002 to the end of 2015, installed capacity has been multiplied by 75 (from 160 megawatts to more than 12 gigawatts) while costs have dropped by more than 30% (IRENA, 2016). Innovation in the industry was encouraged by government financial support, fostering costs reductions and performance enhancement. Technological innovation, as well as innovation in policy-making, finance and business models are expected to make offshore wind a key part of the global energy mix in the next decades.

2.3. Complementarity and substitutability of knowledge elements

Numerous scholars consider that technological invention arises from the recombination of prior and/or new knowledge elements (Schumpeter, 1939; Nelson and Winter, 1982; Henderson and Clark, 1990; Fleming, 2001; Fleming and Sorenson, 2001). According to Schumpeter (1939), innovation consists of combining components in new ways or new combinations. Nelson and Winter (1982, p. 130) observe that "innovation in the economic system […] consists to a substantial extent of a recombination of conceptual and physical materials that were previously in existence." Fleming and Sorenson (2001) take the example of the automobile as combining the bicycle, the horse carriage, and the internal combustion engine, the steam ship as combining the boat with steam power, and the microprocessor as combining the computer's central processing unit with integrated circuit fabrication processes. Following these ideas, we consider OETs to be combinations of existing and/or new knowledge elements or refinements of previous combinations. In a broad perspective, they can be characterized as combining knowledge of the kinetic, chemical and thermal properties of seawater with knowledge about electricity production.

Technological invention is depicted as the search for novel and potentially better (re)combinations of knowledge elements constituting the knowledge base. The knowledge base can be conceptualized as a set of information, competences, and knowledge elements upon which firms draw to resolve technological problems (Dosi, 1982; Nelson and Winter, 1982). Studies in this area focus mainly on how the quantitative characteristics of the knowledge base influence innovation outcomes. Many scholars argue that the size or breadth of the knowledge base (Link, 1981; Griliches, 1986; Jaffe, 1986; Ahuja and Katila, 2001; Zhang et al., 2007; Boh et al., 2014) and the diversity of the pieces of knowledge constituting it (Henderson and Cockburn, 1996; Garcia-Vega, 2006; Quintana-García and Benavides-Velasco, 2008; Strumsky et al., 2011; Carnabuci and Operti, 2013) are key factors to an investigation of inventive activity.

[13] Wind-driven waves, or surface waves, are created by the friction between wind and surface water. Tidal waves are caused by the gravitational pull of the sun and moon on the earth.

In contrast to this dominant focus, some more recent literature examines the structural aspects of the knowledge base (Nesta and Dibiaggio, 2003; D'Este Cukierman, 2005; Nesta and Saviotti, 2005; Yayavaram and Ahuja, 2008; Phelps et al., 2012; Dibiaggio et al., 2014; Guan and Liu, 2016). These authors show that the relationships between the technological knowledge elements reflect the methods developed to use and exploit knowledge (Dibiaggio et al., 2014). "These relationships record the past combination and affiliation of knowledge elements in the process of innovation, and then serve as the flowing and searching channels for knowledge and guide for future potential combination or recombination of knowledge elements" (Guan and Liu, 2016, p. 98). Thus, the relational properties of the knowledge elements included in the knowledge base may affect the search process which in turn, may affect the direction and speed of technological change. In this paper, we study the OET knowledge base using the framework developed by Dibiaggio et al. (2014). The structure of the knowledge base is described as a function of the aggregate level of complementarity and substitutability of its knowledge components.

Following Milgrom and Roberts (1990), Dibiaggio et al. (2014) define two complementary elements as elements whose value or utility increases if they are combined. In other words, these complementary components can be both combined and used intensively in combinatorial search which leads to synergistic effects. Complementary knowledge elements can be used separately unlike interdependent knowledge elements. Substitutable elements are elements that complement the same other elements. More precisely, "substitutability characterizes the extent to which elements share similar properties in their use with other elements and, therefore, the extent to which elements tend to be combined with the same other elements" (Dibiaggio et al., 2014, p. 1583). Substitutable elements may represent knowledge base functional redundancy, or the capacity to use different elements with similar properties. It can be useful in a combinatorial search process to test different competing options in the same context in order to better identify and evaluate the characteristics of the knowledge elements.

The degree of complementarity and substitutability of knowledge elements affects the coherence of the knowledge base (Nesta and Saviotti, 2005). Knowledge base coherence can be defined as "the extent of integration of different elements of knowledge. The more related the elements of knowledge, the more coherent the knowledge base" (Nesta and Saviotti, 2005, p. 129). Increasing complementarity can contribute to stabilizing the technological linkages among knowledge elements, and favor knowledge base coherence. In that sense, knowledge base coherence refers to the overall likelihood to mobilize and implement different knowledge elements in a non-random and complementary manner. High substitutability can allow the testing of different combination alternatives in an immature technological environment -the fluid phase in Abernathy and Utterback's

(1978) model- where several combination options compete with uncertainties as to the result of their interactions. Nesta and Saviotti (2005) point out that firms explore the technological landscape by building various competencies regardless of their relatedness. Although it might affect the overall coherence of the knowledge base negatively in the short run, high substitutability, by allowing the testing of different combination options, enables firms to improve their ability to adapt and avoid becoming locked into a potentially inefficient technological trajectory in the long run. “But as technology matures, preferable or superior knowledge combinations become better identified. Firm may abandon specific, less promising competencies without having to face similar threats while fostering higher levels of technological complementarity” (Nesta and Saviotti, 2005, p. 145). In this perspective, as technology matures, complementarity among knowledge elements enhances. As a result, the likelihood of identifying and selecting relevant combinations increases, as well as the ability to develop R&D activities in a technological landscape based on familiar knowledge combinations (Dibiaggio et al., 2014).

Previous studies based on energy technology patents highlight the existence of knowledge spillovers from past stocks of knowledge on current innovations in energy technologies (Popp, 2002; Johnstone et al 2012; Braun et al., 2010), and flows of knowledge among inventors (Nemet, 2009; Noailly and Shestalova, 2013). Knowledge spillovers across technological domains are essential aspects of the most important energy inventions (Nemet, 2012). However, little work has been done on the combinatorial structure of energy technologies. The present paper is a first step in that direction, and examines the relational properties of the knowledge elements in the OET knowledge base. OETs are part of the new-*versus*-new level of competition and are characterized by a common knowledge base but each technology presents variation in terms of combinatorial solutions as illustrated by the different technical characteristics of solutions for using the ocean to produce electricity. There is evidence suggesting that since hydropower and marine technologies are intertwined with wind technologies and contribute to the knowledge base of these three technologies (Noailly and Shestalova, 2013), complementarity is important for their consistent development. However, high complementarity may be inappropriate in a context of strong maturity differences because it is not compatible with the exploration phase typically characterizing the fluid phase of technology evolution. Thus, a high level of substitutability is more likely to characterize the emergence of immature and risky OETs; it allows for a less coherent knowledge base and a higher level of explorative activity. To identify and understand the evolution of OETs we need to look more closely at the links between the technological knowledge elements of the relevant trajectories.

3. Methodology

3.1. Patent data

We use patent data to trace technological trajectories within the family of OETs and to analyze the characteristics of their knowledge base. Patent data are used to examine knowledge flows in energy since they allow operationalization of the dynamics of knowledge generation and transfer in the energy sector (Nemet, 2012). By definition, patent data measure novel, non-obvious and useable technological enhancements (OECD, 2009). Also, comprehensive data on patents and their citations are publicly available, and include detailed descriptions of technological characteristics and technical domain classification (Popp, 2006). The limitations of patent data are also well known: not all inventions are patented, not all patents are equally important, and the propensity to patent varies across countries and firms. Moreover, the data can be affected by the strategic behavior of some applicants and inventors such as strategic patenting or preference for secrecy. Nevertheless, patents represent the pieces of knowledge contained in the inventive output, and are especially relevant in the case of the energy sector and in the context of climate change (Nemet, 2012).

Patent citations are used widely to proxy for knowledge flows since they point directly to the prior art on which the patent is based, and thus represent a "paper trail" allowing the study of knowledge diffusion (Trajtenberg, 1990)[14]. The limitations to patent data have been well documented: not all citations represent knowledge flows since both inventor and patent examiner can add citations to a patent; self-citation where citations are contained within the same family of patents or group of equivalent patents which have been granted in several different countries for the same invention; and truncation issues (patent age) due to the fact that a full citation history takes decades to establish[15]. Nevertheless, patent citations would seem to be the best available indicator of knowledge flows (Trajtenberg, 1990) since they provide accessible and comprehensive information on the linkages among patents, and thus, are widely used in the literature on knowledge flows (Battke et al., 2016). Therefore, we use patent citations to indicate knowledge flows and patent quality.

[14] For each patent, two types of citations can be identified: 1) *backward citations* are citations made by the current patent, reflecting the knowledge on which the current patent builds (Jaffe et al., 2000); 2) *forward citations* are citations received by the focal patent over time, reflecting the knowledge spillover from the focal patent to follow-on inventions. The number of forward citations also reflects the value of the invention since more valuable patents tend to be cited more often (Trajtenberg, 1990).

[15] Bearing in mind these limitations, we need to check for the share of citations assigned by inventors *versus* examiners using PATSTAT data; we exclude self-citations to obtain the main path; we make no truncations and analyze OET patents over the whole period while recognizing that the most recent patents have had less time to be cited.

In contrast to some other 'environmental' technologies, renewable energy technologies in general and OETs in particular have the advantage that the definition of the related patent classifications allows easy identification of the relevant patents. The choice of the four OET types results in a high quality and representative data sample since targeted patent classes exist for these technologies in the CPC[16]. (See appendix A2).

As already mentioned, we decided to include patents related to offshore wind turbines in the marine environment. Our final dataset includes 19 276 patent families granted between 1900 and 2015 for ocean energy and offshore wind technologies.

3.2. Assessment procedure

In what follows, we adopt a three-step approach. First we analyze the main trends emerging from patent statistics, highlighting how OETs have evolved over time and their reliance on different organizations and countries. Second, we construct a network of citations among OET patents and apply to it the main path algorithm which selects the most important growth stream in a citations network[17]. Thus, we can expect the contributions identified by this algorithm to capture the main technological trajectories characterizing the evolution of ocean energy technologies. This allows discussion of the main characteristics of the OET knowledge base and the possible connections among the different types of OETs. Third, based on the results of the main path analysis, we consider the structural aspects of the knowledge base. We adopt the method in Dibiaggio et al. (2014) to measure the complementarity and the substitutability of the knowledge elements constituting the OET knowledge base.

3.3. Complementarity and substitutability indicators

Each CPC technological class i (with i=1; …; n) is assumed to represent a knowledge element. We obtain a symmetrical 1202×1202[18] matrix for each year between 2000 and 2015. For a given period, the level of complementarity of the knowledge elements constituting the OET knowledge base

[16] Until recently, documents relating to sustainable technologies were scattered throughout the IPC and ECLA/CPC and were not gathered under a single classification. To allow their easier identification, the EPO introduced a tagging scheme known as the Y02/Y04S scheme. Each time a document relating to a sustainable technology is added to its databases, the EPO assigns it as Y02 (for Climate Change Mitigation Technologies) or Y04 (for smart grids) symbol (EPO, 2015). Therefore working with CPC classes to identify OETs is especially relevant, all the more so since the recovery rate between IPC and CPC for the tag Y is higher than 90%.

[17] By computing the total number of paths linking the oldest to the most recent vertices in a citations network, the algorithm maps all possible streams of cumulative growth of knowledge and identifies the most important one.

[18] To restrict the number of codes and thus the size of the matrix, we include only codes with a minimum of 3 occurrences, and likely to span the comprehensive set of codes found in the main path.

(*COMP*) can be calculated as the weighted average complementarity of all elements in the knowledge base:

$$COMP = \sum_{i=1}^{n} \frac{P_i}{\sum_i P_i} C_i \qquad (1)$$

P_i is the number of patents associated to technological class *i*. C_i is an index reflecting the relative complementarity of technological class *i* in the knowledge base. This is calculated as follows:

$$C_i = \frac{\sum_{j \neq i} \alpha'_{ij} P_j}{\sum_{j \neq i} P_j} \qquad (2)$$

P_j is the number of patents associated to technological class *j*. α'_{ij} is the normalized value of α_{ij} ($\alpha'_{ij} \in [0; 1]$):

$$\alpha'_{ij} = \frac{\alpha_{ij} - Min\alpha_{ij}}{Max\alpha_{ij} - Min\alpha_{ij}} \qquad (3)$$

with $Min\alpha_{ij}$ and $Max\alpha_{ij}$ respectively the minimum and the maximum values of α_{ij}. α_{ij} compares the observed frequency of the combination of technological classes *i* and *j* to the expected frequency for random combination:

$$\alpha_{ij} = \frac{X_{ij} - \mu_{ij}}{\sigma_{ij}} \qquad (4)$$

X_{ij} represents the number of patent documents classified in both technological classes *i* and *j*. μ_{ij} is the expected value of random technological co-occurrence and σ_{ij} is its standard deviation[19]. According to equation (4), the degree of complementarity between two technological classes is measured by the number of times that the two technological classes are assigned to a patent document. This calculation relies on the survivor measure of technological relatedness (Breschi et al. 2003; Nesta and Saviotti, 2005) assuming that if the combination of two knowledge elements provides complementarity and synergistic effects, the combination will be reproduced and expanded, while ineffective combinations will tend to disappear. Equation (4) is calculated for all possible combinations.

We replicate and adapt equations (1) and (2) to calculate the level of substitutability of the knowledge elements constituting the OET knowledge base (*SUB*):

$$SUB = \sum_{i=1}^{n} \frac{P_i}{\sum_i P_i} S_i \qquad (5)$$

[19] Calculation of the expected frequency of technological co-occurrence is based on a parametric approach. The distribution of random technological co-occurrence is assumed to be hypergeometric.

$$S_i = \frac{\sum_{j \neq i} \beta_{ij} P_j}{\sum_{j \neq i} P_j} \qquad (6)$$

S_i is an index reflecting the relative substitutability of technological class *i* in the knowledge base. β_{ij} is the cosine index measuring the degree of substitution between technological classes *i* and *j*. It is calculated as follows:

$$\beta_{ij} = \frac{\sum_{k=1}^{n} X_{ik} X_{jk}}{\sqrt{\sum_{k=1}^{n} X_{ik}^2} \sqrt{\sum_{k=1}^{n} X_{jk}^2}} \qquad (7)$$

with X_{ik} the number of joint occurrences of technological class *i* with all other technological classes *k,* and X_{jk} the number of joint occurrences of technological class *j* with all other technological classes *k*. The cosine index is a measure of the functional similarity between technologies which notably is used to evaluate proximity among firms' technological profiles (Jaffe, 1986). According to equation (7), technological classes *i* and *j* are all the more substitutable that they are used with the same set of other CPC codes (because they are used for similar purposes in similar technological developments).

4. Results

4.1. Long term trend

The results show (Figure 3) unequal growth of OET patents since 1900 with four main phases: *(a)* 1900-1930, first take-off of OET patents mainly from individual inventors and public organizations (universities) which became the basis for further development by private firms; *(b)* 1930-1970, sharp slowdown of OET patents due to the powerful exclusion effect of the petrochemical paradigm; *(c)* 1970-1995, increased growth with a peak in the early 1980s (consequence of oil shocks) followed by a downward trend to 1995; *(d)* 1995-present, sharp and continuous rise in OET patents paralleling the huge public investments made to develop offshore wind energy in the transition to a more sustainable paradigm. Thus, in a long term perspective OETs are characterized by cyclical technological change with stages of emergence and re-emergence clearly connected to recurrent tensions in the petrochemical paradigm when energy and pollution rise to the top of political agendas.

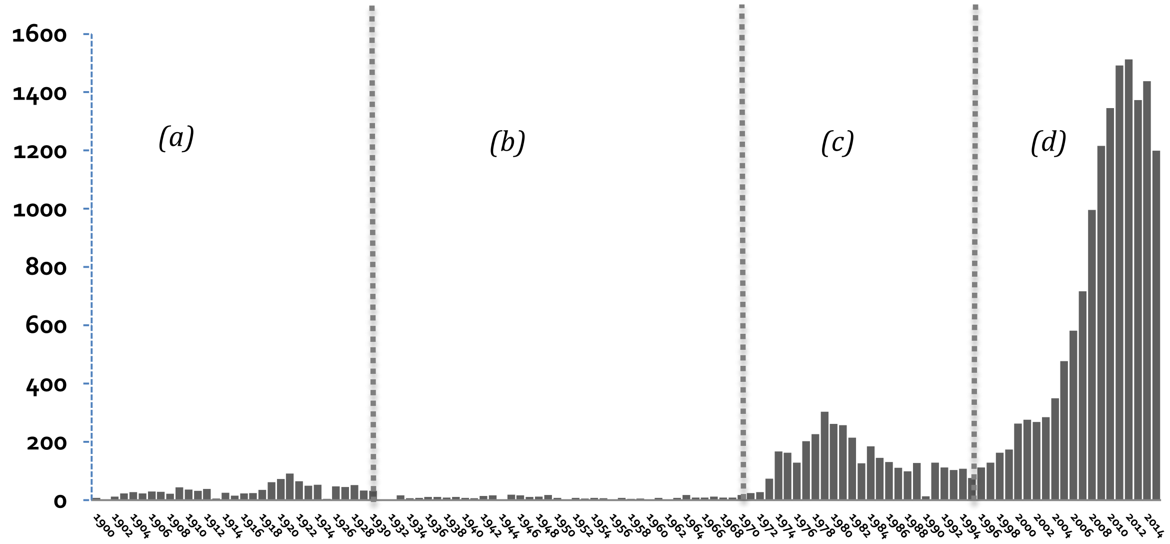


Figure 3: Number of patent families by first priority year for ocean energy technologies over the period 1900-2015

Given the relative immaturity of OETs compared to most other energy technologies much of the focus in terms of barriers to deployment has been on the level and type of support for ocean energy innovation (WER, 2016). Comparison of the fluctuating evolution of ocean energy patents with the intermittent nature of ocean energy funding since the first oil crisis (Figure 4), leads to the assumption that this lack of stability in public support has hindered the development of OETs. According to Vantoch-Wood et al. (2012) (cited in WER, 2016, p. 51), this 'boom and bust' funding cycle significantly interrupted innovation progress.

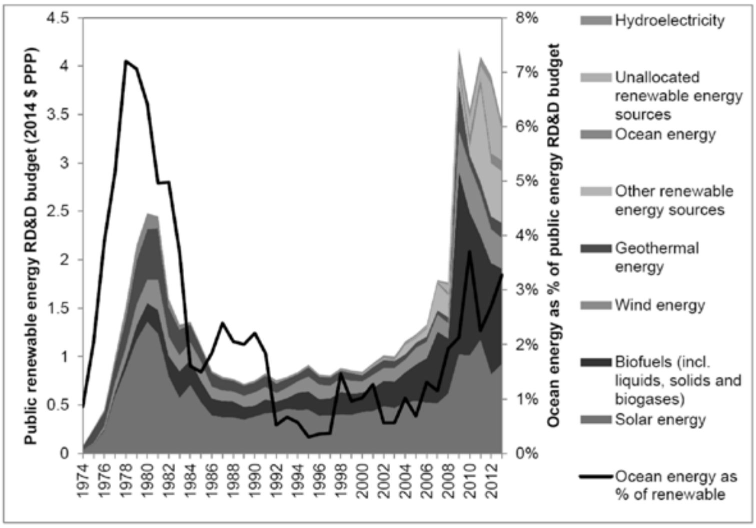


Figure 4: Public energy Research, Development and Demonstration (RD&D) budgets for renewable energy over the period 1974-2013

Source: IEA, 2016.

This long term perspective illustrates the discontinuity in knowledge accumulation in OETs due to the dominance of the established technology in the petrochemical paradigm, and the significant role of energy policy in shaping the old-*versus*-new competition in favor of renewable energy sources in general and ocean energy in particular.

Figure 5 focus on the recent period. It shows the evolution of cumulated numbers of patents between 2000 and 2015 for the technologies under consideration. We observe that the innovation related to OETs increased progressively from 2004 along two main paths: wave and tidal. These two technology sub-groups include the main innovative efforts while offshore wind, OTEC and salinity have increased more slowly over the recent decade. We thus observe unequal development between the various new alternatives, with an emphasis on OETs such as wave energy and tidal energy conversion.

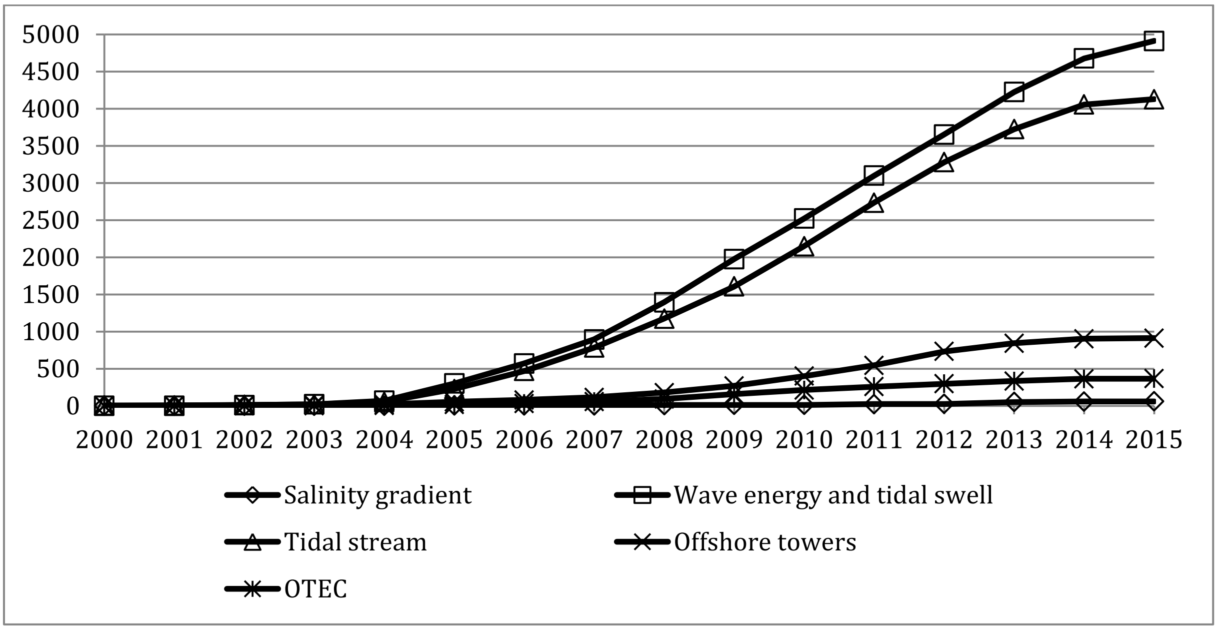


Figure 5: Evolution of OET patent families (cumulated number) by first priority year between 2000 and 2015

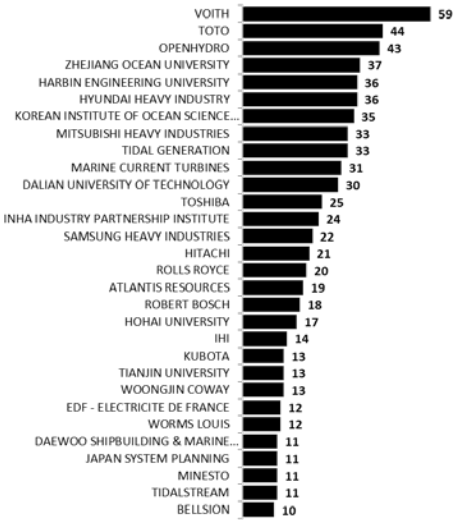
4.2. Main assignees and countries

Figure 6 shows the top OET patent assignees and shows the predominance of large established companies in the energy and shipbuilding sectors. Chinese and Korean organizations are well represented whatever the sub-group considered. Note also the presence of diverse public organizations: public research institutes (universities, Institut Français du Pétrole), engineering schools (Polytechnique Grenoble), generalist electric equipment suppliers (e.g. Samsung), specialized hydroelectric equipment suppliers (e.g. Voith), energy producers (EDF), shipbuilding manufacturers (DCNS) and aerospace actors (Lockheed).

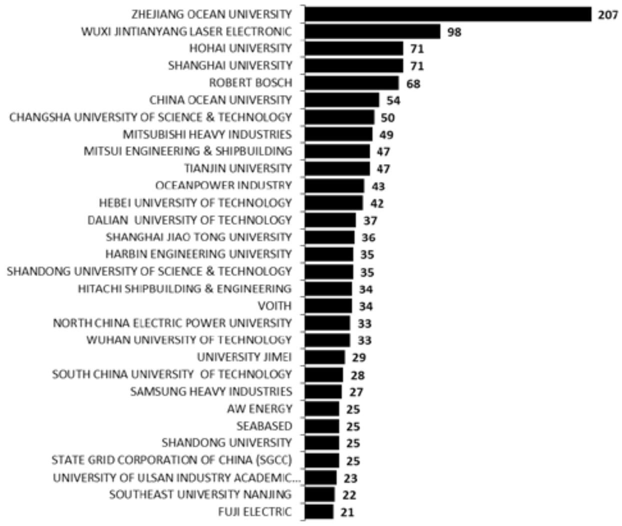
A closer look at each sub-group reveals a difference between wave energy and tidal stream in terms of type of assignee although both technologies show a similar increasing trend. Wave energy is developed mainly by universities in Asian countries but few universities seem to be involved in the development of tidal stream energy (Figures 6(a) and 6(b)). In general, patenting activity in wave and tidal is concentrated in a small number of organizations compared to the other three domains where innovative efforts are spread among a high number of players. Among the most active organizations in offshore wind are some of the largest and most important electric equipment suppliers including Samsung, Daewoo, Siemens, General Electric or Mitsubishi and Hitachi (Figure 6(e)). In the case of OTEC, we observe involvement of major aeronautics (Lockheed) and shipbuilding companies (DCNS) as well as important research organizations including the Korean Institute of Energy Research (KIER), the IFP Energies Nouvelles (the old French Institut du Petrol) and CNRS (French National Research Centre) (Figure 6(c)). In relation to salinity research there are two major Korean organizations among the top assignees; these research organizations (KIER and Hong IK University Research Institute with respectively 25 and 4 patents) are characterized by a tradition of research in energy technologies and marine systems. They are followed by two US private companies, Applied Biomimetic and Ormat, and then Samsung (Figure 6(d)).

Accordingly, OETs exhibit quite different profiles in terms of public or private sources of innovation. Except for wave energy, public organizations are not so well represented. But the fact that OETs are high-risk technologies in terms of performance, cost and operating conditions compared to other mature renewable energy technologies (combined with difficulties in attracting funds) suggests that they should be best served by patient, long-term committed finance, *i.e.* by stable public support (Mazzucato &Semieniuk, 2018). Again with unstable public spending in OETs such as illustrated in figure 4, public sources of finance fail to play a pivotal role in stabilizing the investment volume needed to speed up OET technological progress.

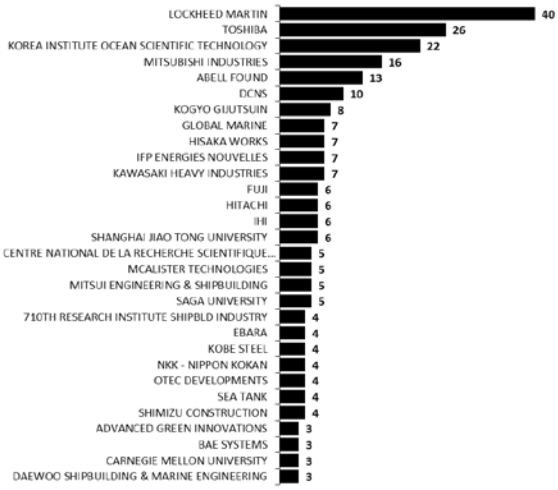
(a) Tidal



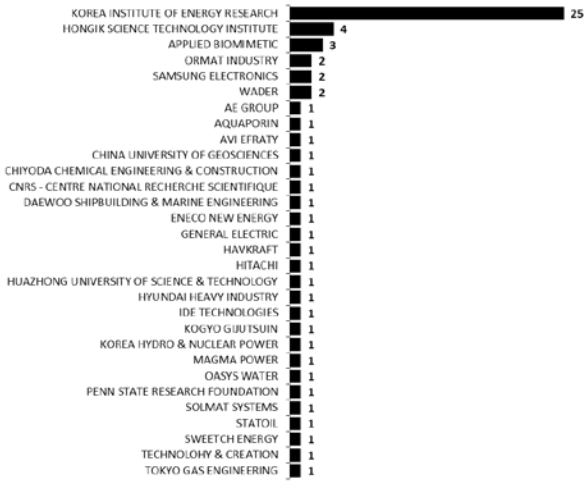
(b) Wave



(c) OTEC



(d) Salinity



(e) Offshore wind

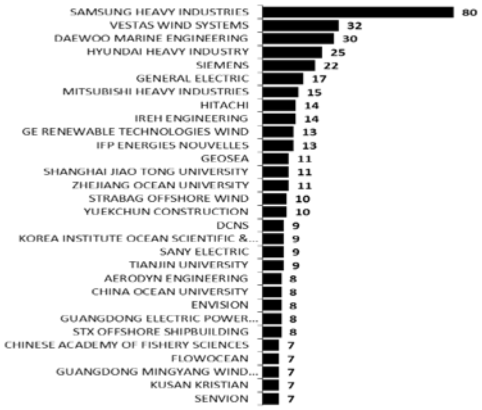
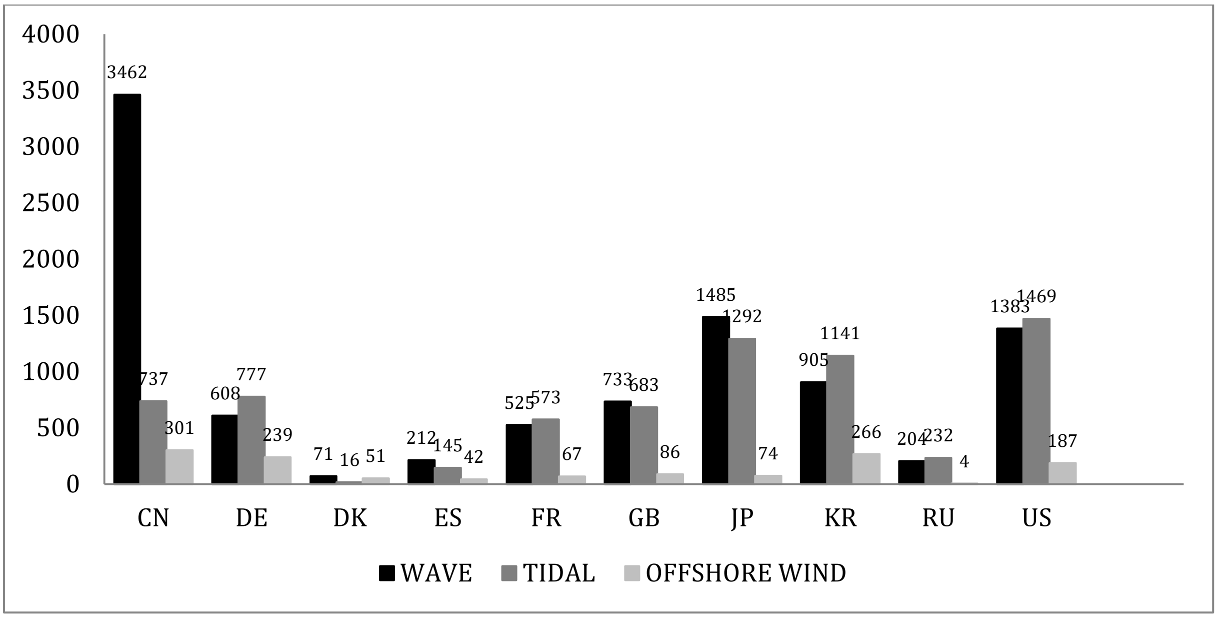


Figure 6: Top patent assignees in each technological sub-group

Figures 7 depicts the number of patent families by priority country. It shows that China, Korea, Japan, and the US are among the top five players. The main European countries namely Germany, Great Britain, France, Spain, Denmark, and Russia are lagging behind. Most countries are characterized by a balanced distribution of patents between wave and tidal, with the exception of China which has a large number of wave patents. Again Chinese universities appear to be the dominant actors in innovations in wave technologies in the recent years. As regards OTEC, Japan and the US take the advantage, leaving behind a first group of followers including China, France and Korea and a second group comprising Great Britain, Germany and Taiwan. Regarding salinity, Korea and the US -though in a lesser extent- are among the top two players. China and the main European countries are not really active in that field. If we look at a bigger picture to apprehend the cumulativeness of technical advances rather than the volume of patents in a particular year, we will use a specific tool: the main path analysis.



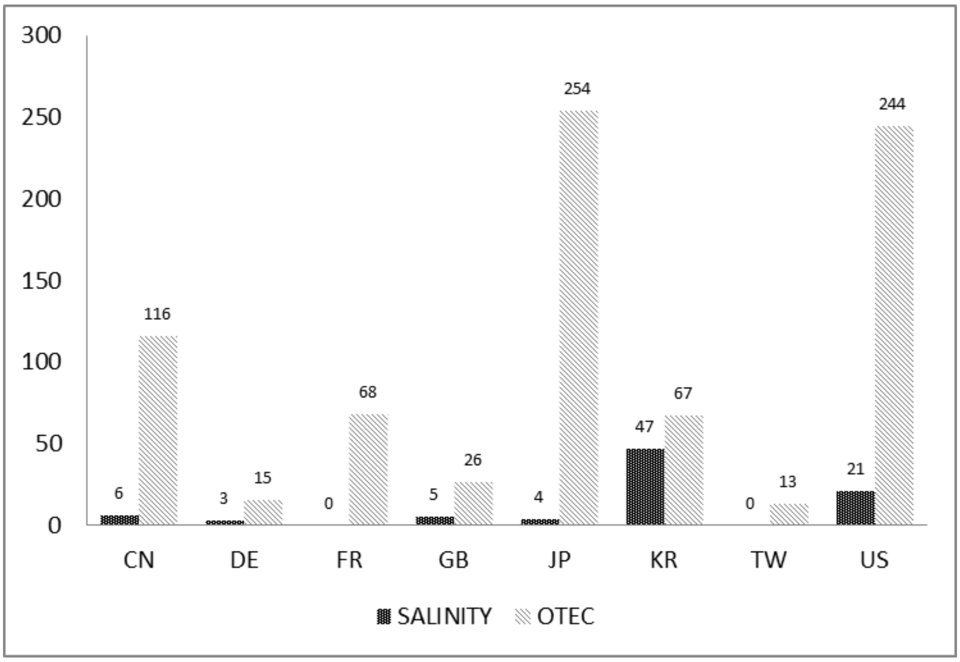


Figure 7: Number of patent families by priority country[20]

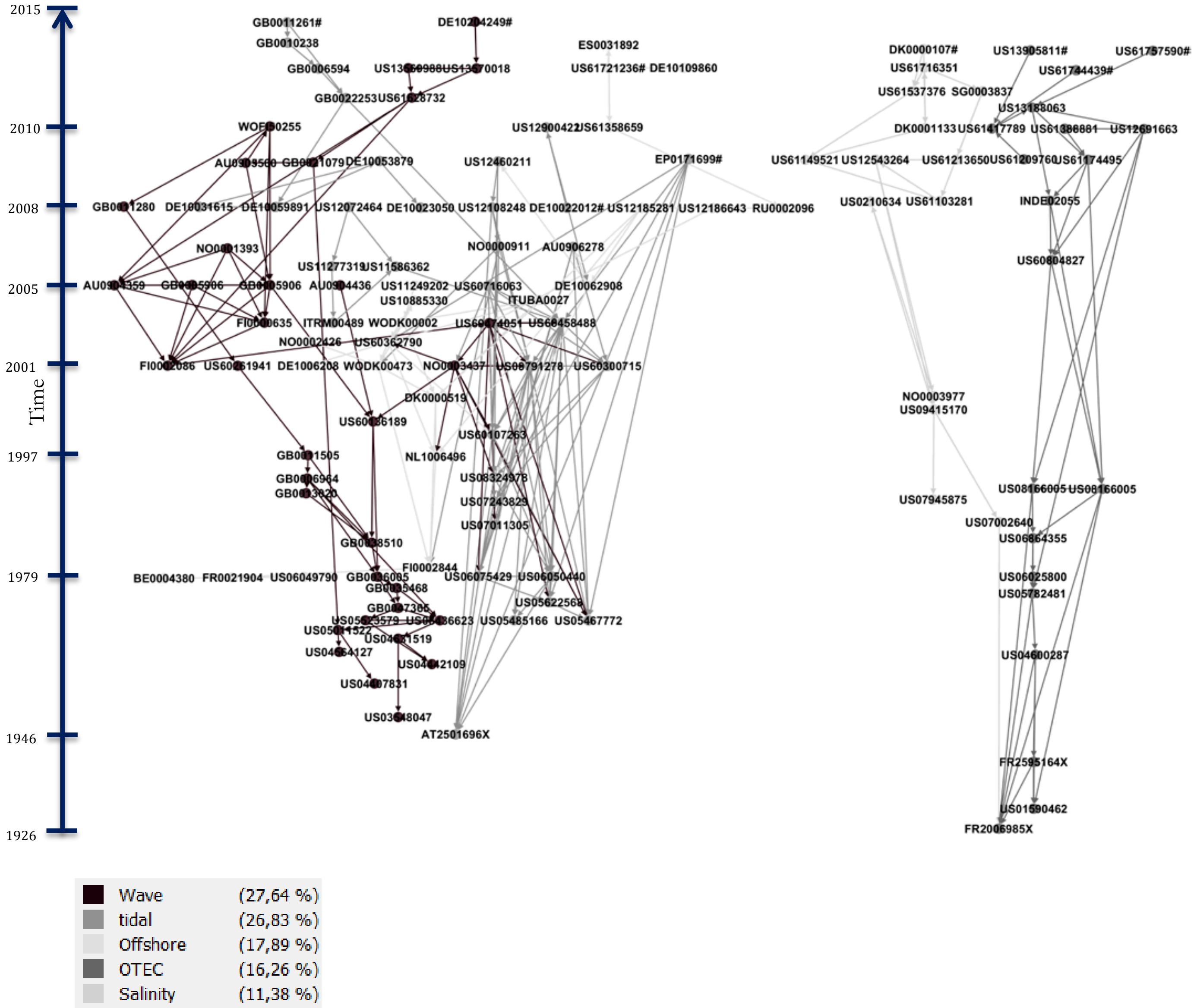
4.3. Main path

Figure 8 depicts the main path that captures the dominant direction of knowledge accumulation that developed along each sub-group of OET. If we start from the bottom of the figure and move along the vertical axis, we can follow the time evolution of each trajectory. There are two distinct blocks of technology: wave/tidal/offshore, and OTEC/salinity. This split into two main separate families depends on the opposition between the fundamental principles of physics versus chemistry. In other words, depending on whether the solutions for harnessing the power contained in oceans and converting it to renewable low-carbon electricity derive from physical sciences or chemical sciences, the knowledge and competencies accumulated over time are quite different.

Within each block or family we observe compartmentalized trajectories with few connections among them. In the first block, salinity and OTEC share a common patent dated 1926 which was granted to the “fathers” of power generation, George Claude and Paul Boucherot, based on ocean energy, for an innovative method and apparatus to obtain power from sea water (1926FR2006985X). Since then, salinity has developed separately from OTEC, and each trajectory has made incremental advances. By focusing on water with different salinity concentrations, the technology on salinity gradients has concentrated progressively on the development of membranes (osmosis, biomimetic) suitable for water extraction. In the case of OTEC, continuous advancements have been made to improve heat

[20] Note that the percentage shares of extended patents in world patents and European patents are respectively: 10.85% and 1.24% for wave, 13.25% and 1.71% for tidal, 24.45% and 7.25% for offshore wind, 1.60% and 0.46% for OTEC, 2.25% and 1.12% for salinity.

exchange systems combining evaporators and condensers, and utilizing large volumes of sea water to produce electrical power.



% of the most influential patent family

Figure 8: Main Paths in OETs. Note: each number indicates the date (priority year), country and file number of the earlier application; # indicates the end of the path

In the other block we can see two main types of connection: wave and tidal on the one hand, and tidal and offshore on the other. In the first case, we observe two pivotal patents related to wave energy (2001NO0003437 and 2003US60474051), granted in 2001 and 2003 respectively which have contributed to increasing the knowledge in subsequent patents for tidal energy. In the second case, we can identify two key patents for offshore wind (2005DE10062908 and 2008US12186643), granted in 2005 and 2008 respectively which have influenced subsequent inventions in tidal energy production. In terms of their topics in each trajectory, the first two deal with water current turbines, *i.e.* technologies for power generation through movements of water and currents. The second two relate to inventions mixing floating type wind power generation technologies and production of hydraulic energy. They combine an offshore wind turbine with a floating device to produce energy from water currents. Analysis of these pivotal patents suggests that – though rare – there has been some hybridization at some point in time which has contributed to the development of the knowledge base of that sub-group of OETs.

Looking at the patent families' country of origin, we observe that the US and Europe, especially Great Britain and Germany, are the most influential countries enabling the development of OETs. This result contrasts with the country distribution of patents granted in the most recent years (Figure 7) where China appears to own a great volume of wave energy patents as well as Japan and Korea that also own a relatively great volume of tidal energy and wave energy patents. Hence, in spite of high patent activity density in Asian countries, the US and Europe still contribute to the building blocks that are critical to major advances in OETs.

Another unexpected result appears when closely looking at the type of patent assignee in OETs: independents are central to the process of technological development in OETs. Figure 9 compares the share that each type of patent assignee, namely independent (IND), private firm (PRIV), public organization (PUBL), private-public organization (PRIV-PUBL) and non-profit organization (NPO) represents in the total number of OET assignees on the one hand and in the main path network on the other hand. We can observe that independent inventors without a corporate or other affiliation, who take out patents in their own name, account for almost half of tidal and wave patents. By contrast patents granted to public organizations represent a small share of tidal energy and wave energy patents. We can wonder why independents contribute so much to key increments to OETs knowledge accumulation despite the risks. One explanation is that independent and firm-based innovations are two types of activity that are complementary (Baumol, 2002). Firms acquire external innovations that complement formal R&D. This dual contribution seems to play a significant role in the process of OETs development and further research would be useful to better understand the demand-based incentives underlying independent inventors.

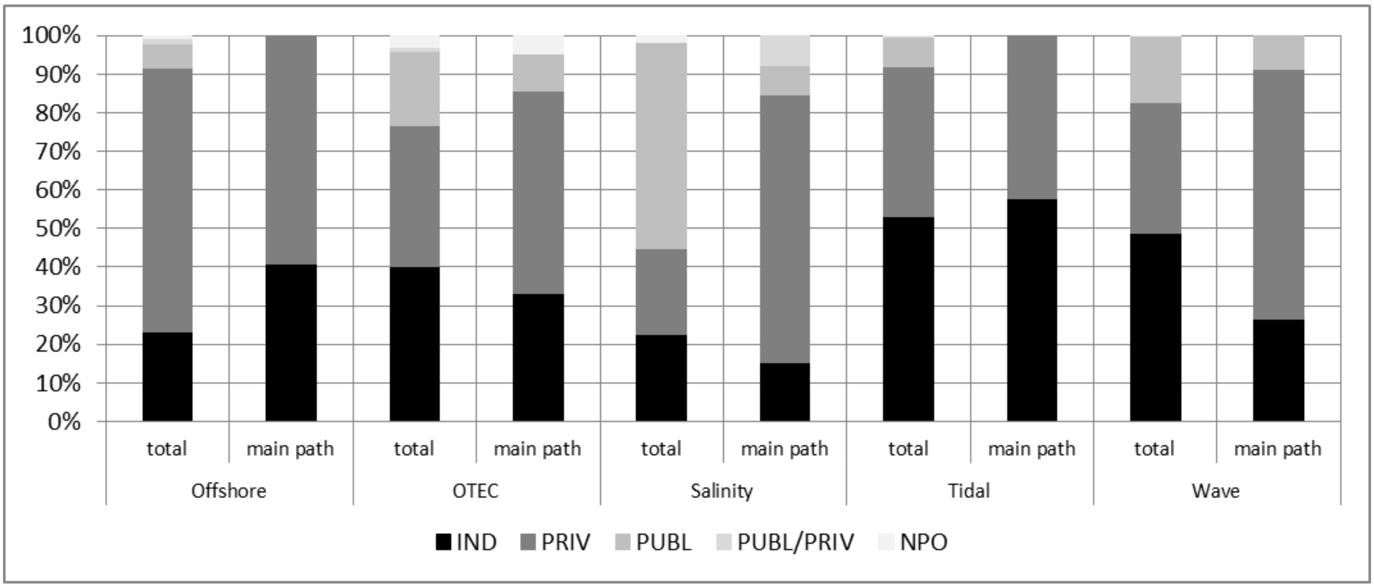


Figure 9: Type of actors in OET patents

Although our analysis focused on the global OET family, we singled out the "physics-based family" (wave, tidal and offshore) since the most important connections over time were internal to that sub-group. For that reason, in what follows, we focus on the "physics-based family" of OETs to further examine the structural aspects of the knowledge base, and analyze the aggregate level of complementarity and substitutability of its constituent knowledge elements.

4.4. Complementarity and substitutability of the knowledge elements

Figure 10 depicts the indicators *COMP* and *SUB* representing levels of complementarity and substitutability of the knowledge elements among wave, tidal and offshore wind. We observe that in the first phase (2000-2006) the overall level of complementarity between knowledge elements was low (0.24 on average) but the overall level of substitutability was much higher (1.19 on average). This corresponds to an exploration phase or 'era of ferment' in the technological environment of OETs which are still immature. Several combination alternatives compete and the effects of interactions remain uncertain or unknown. In the second phase (2006-2009), complementarity increases significantly from 0.26 in 2006 to 1.04 in 2007 while substitutability decreases from 1.66 in 2005 to 0.53 in 2007 so that complementarity becomes persistently greater than substitutability. This coincides with the significantly growing number of tidal and wave patents, concomitantly introducing greater interaction between them. As technological maturity increases, an 'era of incremental changes' occurs during which synergies are exploited while explorative inventions are less favored.

This “scissor effect” suggests greater coherence of the knowledge base that underlies the three considered OETs over time. These results confirm the findings in the literature[21] that in an immature technological environment the overall level of substitutability tends to be higher because technological linkages between knowledge elements have not stabilized, and there is functional redundancy in the knowledge base. In the 2000s, the technological environment of OETs can be described as immature since a large part of these technologies were at an early prototype, R&D, or laboratory stage. In this context, firms develop combinatorial search processes in which several alternative options often compete. From 2006, less competing options are explored progressively and complementarities exploited, suggesting a “*focusing device*” effect, strong until 2008, stabilizing in 2009, and then reducing from 2009 to 2012.

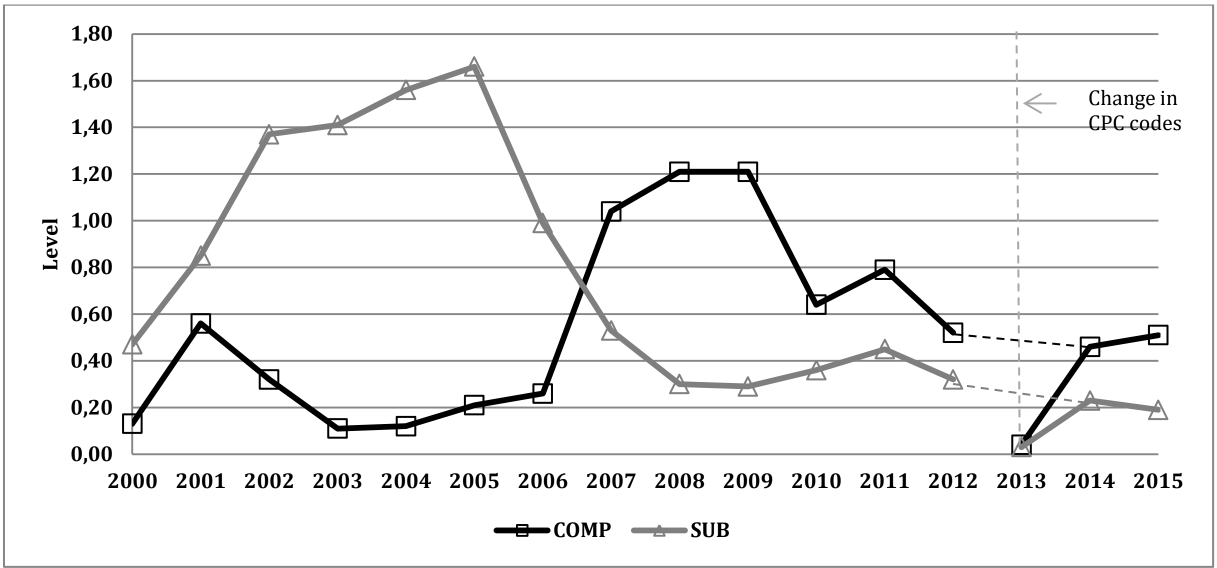


Figure 10: Evolution of complementarity and substitutability of the knowledge elements for wave, tidal and offshore wind

It is noteworthy that the detection of synergistic effects is not linear. Indeed, we observe on Figure 9 that the evolution of COMP -and SUB to a lesser extent- is fluctuating and far from smooth. As already emphasized, this uneven trend is probably a reflection of the ‘boom and bust’ cycle of energy policy funding. However, COMP is declining after 2009 despite important government support intended to accelerate the development and deployment of low-carbon energy technologies, in particular ocean energy. At that time, the number of patents starts declining for all three technologies. However, tidal and wave technologies continue to interact in parallel with a new explorative phase of wind technology which becomes the main source of shake-out (new codes) in the knowledge base (making SUB increase slightly from 2009 to 2011). Such a fluctuating evolution

[21] See on this topic especially Nesta and Saviotti (2005).

echoes the findings in Huenteler et al. (2016a) that the evolution of an industry's knowledge base along a technological trajectory is not a unidirectional process of gradual refinement: the focus of knowledge generation shifts over time among different sub-systems in a highly sequential pattern whose order is influenced strongly by the design hierarchy. For the three OETs considered, the focus of knowledge generation shifted from the technology's core components aimed at harnessing the power of the oceans, to the technology's periphery components oriented towards grid integration, power quality, and control, operation and maintenance. In the case of wave technology, the World Energy Council (WEC, 2016) deplores the premature focus on full scale demonstration which has resulted in an emphasis on device-level *versus* subcomponent innovation (e.g. power take off, prime mover, control system). This has led to a wide-range of characteristically distinct wave energy devices based on different components, delaying the design consensus that is key to commercialization (Magagna et Uihlein, 2005).

Finally, in 2013, the Cooperative Patent Classification (CPC) system -EPO and USPTO- made a change to the codes being used resulting in the reclassification of all patent documents. The mechanical breaking down of the codes generated a change of scale in the levels of the two key indicators under scrutiny (COMP and SUB) requiring us to recalculate COMP and SUB taking account of the new nomenclature. Though we cannot compare the values for each indicator before and after 2013, we observe that starting in 2013, COMP continues to show a slightly growing trend and remains significantly superior to SUB which exhibits a downward path. Each indicator is in line with the previous trends: synergies continue to be exploited, indicating continuous coherence of the knowledge base between wave, tidal, and offshore wind technologies. However, the level of COMP remains low while the level of SUB is declining. This may be symptomatic of the lack of ability to further exploit complementarity due to the difficulty to find a design standard for the technology's periphery components.

5. Discussion and conclusion

Analysis of the knowledge base underlying OETs requires some comments and suggests some implications for policy. First the fact that the knowledge base of OETs is split into two main separate families, one deriving from the physical sciences and the other from chemical sciences, suggest independent research activities and dissimilar competencies. In terms of policy implications, this calls for a partial unbundling of the supposed homogeneous group - OETs. Separate R&D programs that take account of different paradigmatic families would seem more appropriate. However, those patent links connecting tidal, wave and offshore wind within the physics-based family of OETs should also be considered by energy policy since their development may depend not only on their own particular characteristics and maturity levels but also on the complementarity of technological knowledge among those three technologies.

Second, analysis of the relational properties between tidal, wave, and offshore wind technology knowledge elements shows increased knowledge base coherence over time. This is consistent with prior work (Nesta and Saviotti, 2005; Dibiaggio et al., 2014). However, our results show also that detection of knowledge synergies is fluctuating and gradual over time. They suggest that the structure of the OET knowledge base is affected by cyclical energy funding support but also by shifts in the focus on knowledge generation among different sub-systems. For the three OETs considered, the knowledge generation focus has shifted from the technologies core components for harnessing ocean power, to the technology's periphery components oriented towards grid integration, power quality, and control, operation and maintenance. In terms of policy implications, bridging organizations active in the core technology, and organizations active on the periphery are needed to achieve a dominant design which would facilitate commercialization. The hierarchical approach derived from definition of a dominant design as the standard for the technology's core components (Murmann and Frenken, 2006) requires rapid evolution of the design of certain parts of the system and turbulent industry dynamics, and stability in the design of other parts of the system. In our case, ocean energy conversion design is stable but electrical connection, quality control, and maintenance are still evolving and require appropriate public support. If coordination of different types of financing in the deployment phase proves to be essential for the renewable energy sector in general (Mazzucato & Semieniuk, 2018), it is all the more true for those high risk ocean energy technologies characterized by concomitant evolution of sub-system design. Such a coordination also needs to go together with stability of funding over time since, as already observed for renewable energy technology, risk exposure of financial actors will be much higher, on average, in the case of investment in relatively untested immature technology in a country prone to swings in its policy support than in the case of investment in a mature technology in a country with stable policies (Mazzucato &Semieniuk, 2018). In Europe, those two conditions (coordination and stability of funding) are clearly deficient in the underlying long term development of OET.

Third, tidal and wave energy are the most advanced types of OET and have been supported by important efforts conducted by Chinese universities. In the context of our empirical results of low level of complementarity and declining levels of substitutability, Chinese dominance raises risk of loss of diversity and premature lock-in. Recent policy initiatives and mechanisms in the European Union to ensure that OETs will become cost-competitive in the short term, are crucial to support technology leapfrogging (Goldemberg, 1998) and avoid a similar situation to what happened in relation to Chinese solar panels in the context of the solar photovoltaic industry (Fu, 2015).

Overall our results suggest that OET innovative activity is characterized by a fluctuating complementarity of technological knowledge which is constraining the emergence of a dominant design. This confirms that maintaining diversity of innovation and learning processes while taking account of complementarity characteristics is of vital importance for the development of renewable energy technologies, especially for those high-risk ocean energy technologies.

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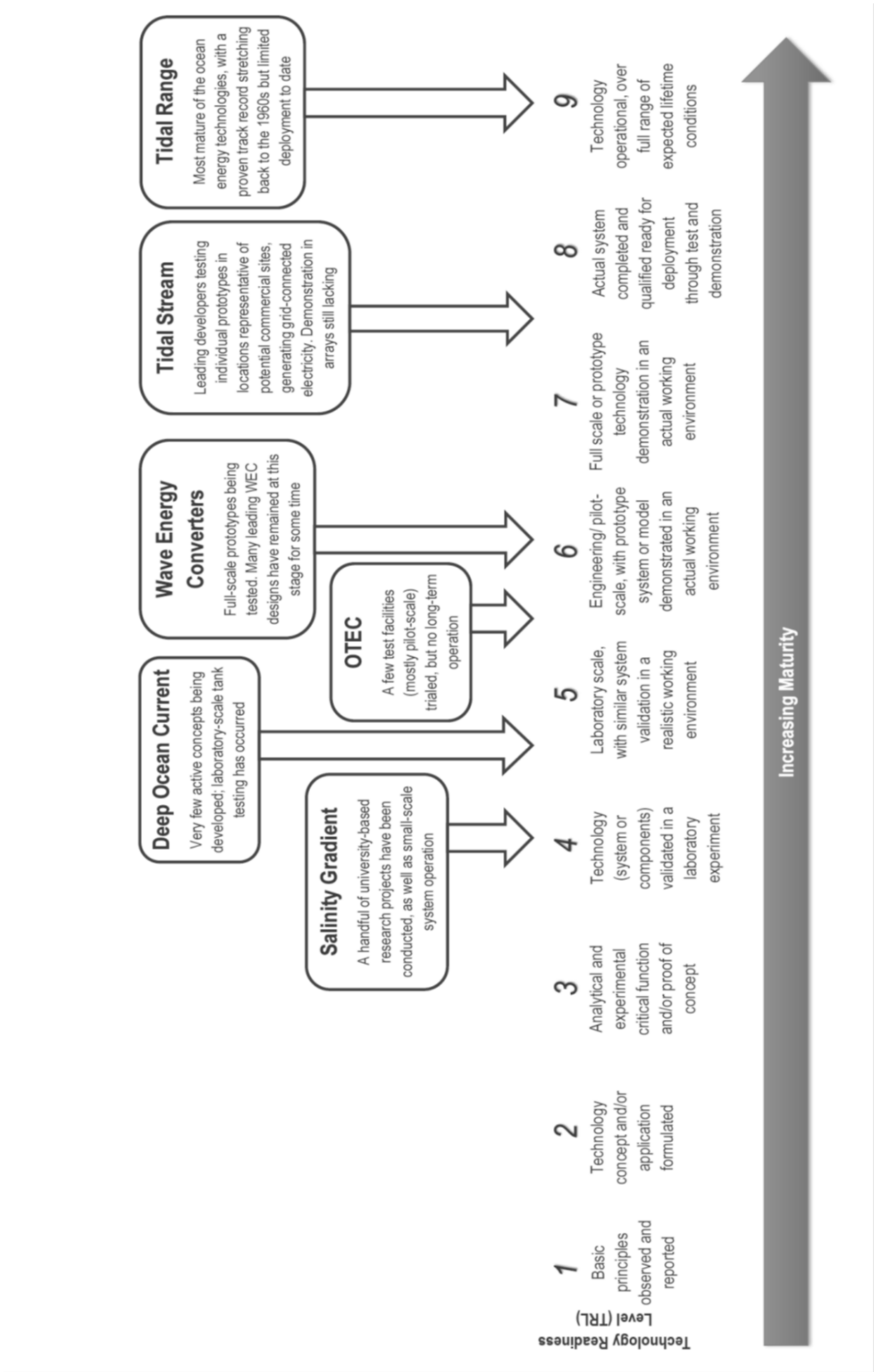
Appendix

A1. Ocean energy technology readiness (IRENA, 2014)



A2. CPC (Cooperative Patent Classification) codes for ocean energy technologies and offshore wind

		Class and subclasses
Reduction of greenhouse gases (GHG) emission, related to energy generation, transmission or distribution		*Y02E*
Energy generation though renewable energy sources		*Y02E 10/00*
Ocean energy technology		
	Salinity gradient	Y02E 10/36
	Ocean thermal energy conversion (OTEC)	Y02E 10/34
	Wave energy or tidal swell or oscillating water column	Y02E 10/38 or Y02E 10/32
	Tidal stream or damless hydropower	Y02E 10/28
Offshore wind		
	Offshore towers	Y02E 10/727

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Avenue Léon Duguit
33608 PESSAC - FRANCE
Tel : +33 (0)5.56.84.25.75
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