# The multi-spatial dynamics of niche trajectory: the case of wave energy technology

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**Abstract**
This paper proposes that niches, as protected spaces where technologies are developed and articulated with societal needs, transcend territorial boundaries, encompassing communities and actions that span several spatial levels. To support this assertion the paper build on the socio-cognitive perspective to niche development and extends it introducing a new dimension - space - broadening and "spatializing" the concept of technological niche. This framework is applied to the case of the wave energy niche. Empirical research combines a generic analysis of the construction of an "overall niche space", with a detailed analysis of the processes taking place in Portugal, which was one of the pioneers in the field. The results confirm the niche multi-spatial dynamics, showing that it is shaped by the interplay between a niche relational space constructed by actors' actions and interactions, and the territorial effects introduced by their embeddedness in particular geographical and institutional settings.

**Keywords:** niche dynamics; space; wave energy technology; strategic niche management; socio-cognitive perspective; Portugal

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**Highlights**

Protective spaces where technology is developed and articulated with societal needs can transcend territorial boundaries

Framework that extends the socio-cognitive perspective to niche development introducing explicitly space as a new dimension

Technological niche is constructed by actors' activities and interactions in and across different spatial levels

Niche dynamics: interplay between an actor constructed relational space and the effects of actors' territorial embeddedness

Non-linear trajectory of wave energy technological niche found to be shaped by processes at these different levels

## 1. Introduction

The spatial dimension has recently started to receive greater attention in socio-technical transitions research (Coenen et al, 2012, Raven et al, 2012). But despite the advances at this level (Hansen and Coenen, in print), the literature on niche formation and development still frequently associates the niche to (narrow) territorial boundaries and localised networks. However, this is not necessarily the case (Raven et al, 2012): some technological niches effectively transcend boundaries, encompassing communities and actions that span several spatial levels, a type of behaviour that is still imprecisely captured by the niche literature. In this paper we develop a conceptual framework that intends to provide a more explicit treatment of space in niche development and apply it to the case of the wave energy technological niche.

The process of niche development and breakthrough has been addressed by the strategic niche management literature (Kemp et al, 1998; Schot and Geels, 2007; Verbong et al, 2008). Recent developments in this literature have moved beyond the focus on individual projects, towards a more encompassing framework that conceptualises a non-linear trajectory along which the emerging field is being structured through a socio-cognitive process (Geels and Raven, 2006; Raven and Geels, 2010). This perspective has provided significant contributions to an understanding of the complex processes that occur in the niche space, both by focusing on the importance of sequences of local projects that build on each other over time; and by introducing the notion of a socially and cognitively constructed "global niche level". From a social perspective, the global niche consists of the global network that encompasses the emerging community. From a cognitive perspective the global niche consists of increasingly articulated and stable global rules and expectations, which are created through dedicated efforts aiming at the formalisation and aggregation of contextual knowledge generated in local experiments, transforming it into abstract, generic knowledge and lessons that can be shared by the community and base an agenda for the field (Geels and Deuten, 2006).

Although spatial issues (geographical and relational) are often implicit in the discussion of the processes that occur in or between the specific local experiments and the more abstract global niche level, space is not explicitly assumed as a relevant dimension, and its implications for the conduction of the niche processes are not explored. This absence is criticised as reducing the explanatory power of the socio-cognitive framework (Coenen et al, 2012).

The objective of this paper is to explicitly introduce the spatial dimension in the analysis of the processes being conducted as part of the trajectory of technological niches. Thus, our contribution is to combine the approach to niche development that addresses the niche as a relatively abstract space, with an approach that puts some "flesh" into this abstract space, by introducing in the analysis the places where the different processes occur and the spatial scope of the relations that are enacted between actors involved in them. Following this approach we define an "overall niche space" that encompasses and spatializes the processes described in the socio-cognitive framework as taking place at both "local" and "global" levels. This enables us to retain the powerful notion of a niche space that transcends individual experiments and territorial boundaries, but also to strengthen it, by grounding it on the actions being developed by niche actors in and across different spatial levels.

This framework is used to analyse the process of development of a technological niche around wave energy conversion. Wave energy is one of the less mature renewable energy technologies, exhibiting a very slow development when compared with other renewables (Falcão, 2010, IRENA, 2014). However, wave energy advocates have managed to convey a vision of future benefits, creating and expanding a community that is prepared to commit attention and resources and to engage in learning processes (OES, 2002-2014). In other words, they have been able to set-up a technological niche and sustain its activity over a long period of time. This niche encompasses activities and networks that span territorial boundaries and have displayed, from start, a strong multi-spatial dynamics. Thus, it provides an interesting setting to investigate the complex spatial processes at work in niche formation and development.

For this purpose, we start by examining how an "overall niche space" in wave energy was spatially constructed over time. Then we look in greater detail into the processes that took place in a country – Portugal - that was among the pioneers in this field, and whose actors have been, from very early stages, engaged in the activities conducted at various spatial levels (OES 2002-2014). This analysis is set in the context of the "overall niche space", of which the activities conducted in Portugal are seen as an element. It enables us to examine in greater depth the niche internal processes and its interactions with the dominant energy regime, in order to answer to the following questions: i) how niche development is shaped by processes taking place at different spatial levels; ii) which is the interplay between territorial and relational elements of space in niche development.

The paper is organised as follows. In section 2 we review the relevant literature and develop a conceptual framework. Section 3 details the approach and methodology for the empirical research on the wave energy technological niche. The results are presented and discussed in section 4, where we start by providing a brief characterisation of the overall niche space and subsequently analyse in greater detail the Portuguese case. This is followed by a discussion of key findings. The paper ends with a conclusion.

## 2. Conceptual framework

### *2.1 Niche construction and development*

This paper addresses the processes affecting the formation and evolution of the technological niches where promising but still underperforming technologies are being developed (Kemp et al, 1998). Technological niches can be defined as protected spaces where technologies and user specifications are still unstable and where the technology-specific structures (actors, networks, and institutions) are still in the process of being created and aligned (Schot and Geels, 2007). These spaces provide an environment that not only shelters the technology but also nurtures it (Smith and Raven, 2012). They allow for experimentation in a societal context, which permits improvements in technological performance and enables the alignment of the technology with user needs and institutional structures (Geels, 2002; Kemp et al, 1998). The final goal is enabling the technologies to become competitive and break out of the niche. Such outcome and the ways in which it may be achieved depend both on processes internal to the niche, and on the way niche processes link-up with developments taking place in the regime and also at landscape level (Raven, 2006; Schot and Geels, 2007).

The internal processes that are critical for the formation and development of technological niches have been put forward by the early proponents of the Strategic Niche Management (SNM) approach (Hoogma et al, 2002; Kemp et al, 1998). These authors identify socio-technical experiments as the locus for niche formation and development and outline three main processes whose interplay might lead to niche upscale and breakthrough: voicing and articulation of expectations; formation of networks of supportive actors; enactment of learning processes, about technical and non-technical aspects. Consistent policies are an important sheltering element and stability of support is critical for achieving long-term results (Jacobsson and Lauber, 2006; Verbong et al, 2008).

Subsequent developments have attempted to address some limitations of this early approach (Schot and Geels, 2008). One of these concerns the excessive focus on niche internal processes. Thus, research has addressed the implications for niche development and breakthrough of its linking-up with the regime within which it emerges and the modes this may assume (Raven, 2006; Smith and Raven, 2012).

Another limitation concerns the learning processes and the way they can contribute to strengthening the niche trajectory. New contributions came from the application of a socio-cognitive evolutionary perspective on technology emergence to niche development (Geels and Raven, 2006; Raven and Geels, 2010). This resulted in the distinction between local experiments (individual projects enacted by local networks) that generate contextualised knowledge, and a global niche level where abstract, generic knowledge is generated, taking the form of shared cognitive rules (problem agendas, heuristics, abstract theories and models). The transformation of contextualised knowledge into generic lessons and cognitive rules requires dedicated aggregation activities that bring together lessons from multiple projects, codifying them and articulating field-level agendas. These agendas need to be subsequently translated to local projects, a process also requiring dedicated efforts (Raven et al, 2011). This approach also clarified the relation between learning and expectations and the (non-linear) evolution of the niche trajectory (Geels and Raven, 2006).

### *2.2 Space and niche development*

These theoretical developments permitted to advance our understanding of the process of niche formation and development. But one further limitation - the treatment of space in niche processes – is still unsatisfactorily addressed, a problem that is transversal to the socio-technical transitions literature (Coenen et al, 2012; Spath and Rohracher, 2012).

A new research stream on the "geography of sustainability transitions" (Hansen and Coenen, in print) provided some contributions in this direction. One concerns the need to contextualise transitions, that is, to put greater emphasis on the territorial and institutional embeddedness of the processes taking place (Coenen et al, 2012). This perspective was applied to the SNM approach (Coenen et al, 2010). Particular emphasis was put on the role of proximity in local niche experimentation, conceptualising proximity as encompassing social, cognitive or institutional aspects (Boschma, 2005) and stressing their importance in the conduction of niche internal processes. This had the advantage of highlighting the critical role played by specific local circumstances - institutional environments, policies, actors – and agglomeration effects. But it also implicitly associated niche to local experimentation and, therefore, tended to confine the niche to a territorially bounded place and the network formed around it.

Other contributions came from research that explicitly considered that transitions take place at different spatial levels - assuming space in territorial and relational terms - and thus, that "localised" activities are in fact subject to local and non-local influences through the position of actors in networks operating at (or spanning) diverse levels (Markard and Truffer, 2008; Binz et al, 2014; Spath and Rohracher, 2012). This approach was namely developed by the technological innovation systems (TIS) literature, which has introduced the notion of "global TIS" (Binz et al, 2012). Although the focus of this research is frequently on how new regions/countries adopt maturing technologies that are already diffusing (Binz et al, 2012; Gosens et al, 2015; Quitzow, in print), the notion of a system that transcends territorial boundaries is also useful in the case of emerging technologies (Binz et al, 2014). In particular, the role attributed to networks in linking actors across spatial levels (Binz et al, 2014; Wieczorek et al, in print) is especially pertinent in the case of less structured systems such as technological niches, whose development is largely supported by the efforts of an evolving community (Geels and Raven, 2006).

This view is also present in recent attempts to incorporate a spatial scale in the multi-level perspective (MLP) to socio-technical transitions (Raven et al, 2012). It is recognised that "there is no reason to conflate the MLP levels with specific territorial boundaries" since they "refer to processes with different temporal dimensions and modes of structuration that could each have a variety of spatial positionings and reach" (Raven et al, 2012: 64). This is namely the case for niches: even if "social networks are less extensive, less stable, expectations more fragile and learning processes are less institutionalized" (idem), it is recognised that they are not necessarily only local. Similarly regimes, with which niches link-up and interact, are not necessarily homogeneous and may incorporate local variations.

In spite of this, the niche literature has not yet managed to fully linking niche processes to this spatial behaviour. One important advance concerns the notion that different local niches can "become (inter)nationally connected through existing or new networks" (Raven et al, 2012: 71). But the emphasis is on how *separated* niches connect, not assuming (at least explicitly) that, in some cases, the niche itself can be a space where internal processes and niche-regime interaction take place simultaneously at different spatial levels.

### 2.3 The multi-spatial dynamics of niche development

In order to address this question we draw on the advancements to SNM provided by the socio-cognitive perspective (Geels and Raven, 2006). This approach introduces two notions that support a broader definition of "niche space": one is the presence of sequences of local projects that may occur simultaneously or build on each other over time, adding-up to the technological trajectory; the other is the concept of a "global niche level" that, according to these authors, effectively corresponds to the technological niche (Raven and Geels, 2010: 89).

This global level is defined along a social and a cognitive dimension. In a social dimension, the global niche is defined as the network that encompasses the emerging community engaged in the development of the technology, including actors involved in local projects and actors not directly involved but providing relevant resources. In a cognitive dimension, the global niche is defined by the cognitive processes that enable the formalisation and aggregation of contextual knowledge generated in local projects, in order to turn it into abstract, generic knowledge that can be shared by the community. Moreover, the analytical distinction between different types of cognitive activities – from problem solving at local level to aggregation at a global level – is described as leading to a division of cognitive labour between actors active in local projects and actors (also or exclusively) engaged in aggregation activities.

This approach also provides some insights into the relational processes that support the construction of a "global level" (Geels and Deuten, 2006). One is the formation of networks that facilitate circulation between projects and the development of a sense of community among the actors in the field. Another is the emergence of actors that have a central role in aggregation activities: intermediary actors that speak for the field. These are often collective organisations (e.g. professional societies, industry associations), but can also be actors that travel between local projects. Finally, there is the creation of dedicated infrastructures, i.e. specific arenas that serve as setting for the circulation of ideas and their discussion across the community, such as seminars or conferences and dedicated journals.

While the main focus of these authors is on providing a conceptual explanation of how the interactions between learning processes, expectations and social networks gradually contribute to niche development trajectory (Geels and Raven, 2006), this approach equally provides a comprehensive and integrated view of the variety of actions and interactions enacted by the actors involved in these processes. These actors are regarded as a community and their activities as part of an overall effort towards niche upscale and breakthrough, thus supporting the notion that the technological niche is, in fact, the overall space where these efforts take place.

The technological niche can thus be described, from a relational perspective, as the combined efforts of this overall community in developing individual projects that generate new local knowledge, in conducting a variety of activities to create and share generic knowledge and to (re)define and agendas and visions, and in the transmission of the outcomes of these efforts, both within the community to feed new individual projects and outside it, in order to attract new members and additional resources.

However, the activities and the actors/networks that enact them remain largely a-spatial. Thus, this approach has been criticised for not explicitly addressing "the interdependence of niche processes with specific institutional configurations in space" (Coenen et al, 2012: 973). In fact, while different spatial scales of operation are implicit in the distinction between networks that are formed around local projects and those that perform aggregation activities; space is not explicitly assumed as a relevant dimension and its implications for the conduction of the niche processes are not explored.

Thus, a further step is required to understand the processes being conducted in this overall niche space: to explicitly introduce the spatial dimension in the niche analytical framework. This is in line with the attempts to introduce a spatial scale in the MLP, where it is assumed that "actors, institutions, beliefs and practices at all levels are embedded and entwined in broader transnational and sub-national spaces of innovation" (Raven at al., 2012: 69). These authors also call the attention to the distinction between an absolute (territorial) and a relative

(relational) spatial scale, arguing that the latter, which is “socially constructed through networks of actors and cut across territories” (idem: 70), has a greater explanatory power.

In this paper we attempt to ground the socio-cognitive perspective, by introducing the idea that the niche processes described, either “local” or “global”, are conducted by actors: i) that belong to, or are temporarily located in places – i.e. specific territorial settings, whose features can influence both the actors’ behaviour and the outcome of the processes (Coenen et al, 2012) – thus explicitly addressing the territorial dimension of space; ii) that are connected in a variety of ways across those territorial settings (Binz et al, 2014), in order to pool knowledge and experiences and/or share lessons; may even operate in territorially disintegrated networks (Bulkeley, 2005) with a view to conduct (field-level) aggregation activities; and that the particular spatial distribution of these networks is not indifferent (Hansen and Coenen, 2014) – thus making more explicit the relational dimension of space.

Thus we combine an approach that addresses the niche as a relatively abstract space where technology is being developed through socio-cognitive processes, with an approach that grounds this abstract space, through the contributions of geography, i.e. by introducing in the analysis the places where the different processes take place and the spatial scope of the relations that are enacted between actors involved in them.

More specifically, we apply this approach to the activities taking place at the local project level and those leading to the construction of a global level. Local projects – which we prefer to label as “individual experiments” to avoid the geographical connotation of “local” - are likely to be conducted in specific locations with particular territorial characteristics (Spath and Rohracher, 2012). However, they can encompass one place or multiple, as when an experiment is physically distributed. Similarly, they are conducted in networks that may include only actors originating from the actual experiment location(s), or also involve actors from other locations, through a variety of connections with different purposes. Moreover, some actors may have moved from projects in other locations or involving other networks, thus being carriers of different knowledge and experiences (Rosenkopf and Almeida, 2003).

In what concerns the activities that configure the “global level”, their nature suggests that they will be less territorially embedded. In fact, it is expected that dedicated aggregation activities will occur in transnational or supra-national networks, and that the knowledge produced will also flow across these networks. The literature on transnational networks (Coe and Bunnel, 2003; Bulkeley, 2005) provides insights into two types of networks that may be in operation at this level. Because exchanges in technological niches are largely concerned with knowledge, networks are likely to assume the form of epistemic communities, where cognitive and (temporary) social proximity led to the development of shared meanings and communication codes (Breschi and Lissoni 2001). In addition, transnational advocacy networks, where a broad range of actors with shared values and a common discourse work together to achieve specific outcomes at an international level (Bulkeley, 2005), also emerge as potentially relevant. The “intermediary actors” that integrate those networks are also likely to originate from different locations and have different types of experiences, and they may be operating simultaneously at several spatial levels.

However, the division of cognitive labour in the niche community (Geels and Deuten, 2006) will mean that some actors will have a greater role in the conduction of the global learning processes and the definition of field-level agendas and visions. Despite the less territorialised nature of aggregation activities, aggregation networks may be more frequently composed of actors from the most active locations, which may also tend to host discussion arenas and any physical infrastructures created. These field-level activities remain partly grounded on

territorial contexts, through the actions and interests of the actors that compose them (Nedeva, 2013). This can have implications for the way generic knowledge is produced and is circulated and shared across the community. Moreover, the way the outcomes of these learning processes are translated into new local projects may also be influenced by local contextual conditions (Raven et al, 2011). Thus, even if the “niche space” transcends territorial boundaries, territorial level effects remain important. A full understanding of niche behaviour will, therefore, require some consideration of the interplay between territorial conditions and the global niche processes.

The above discussion provides a more multifaceted perspective of the niche as a complex space that transcends individual experiments and territorial boundaries, and contributes to define more precisely the spatial dimensions of niche development. The technological niche can therefore be described as a (frequently reconfigured) “overall space” that encompasses a variety of actions and interactions enacted by a diversity of actors that operate at and/or span different spatial levels. This “overall niche space” is expected to have a particular spatial dynamics, which results from the interplay between: a niche relational space constructed by niche actors along their niche development efforts; and the territorial effects introduced by the embeddedness of these actors and their actions in particular geographical or institutional settings. The niche trajectory is expected to be shaped by the processes taking place at these various levels.

## 3. Empirical Research: approach and methodology

### 3.1 Research approach

The explanatory potential of this extended framework is explored through the empirical case of the wave energy technological niche. The analysis is conducted at two levels. We start by addressing, in general terms, the formation of an “overall niche space”, characterising its actors and dynamics in and across a variety of locations. Then we look at the process in greater detail from the standpoint of a country – Portugal - that was among the pioneers in the construction and attempted upscale of a niche around wave energy conversion and whose actors were from early stages engaged in niche development activities conducted at various spatial levels. The Portuguese case enables us to further explore how niche evolution is shaped by cognitive and social processes taking place at different spatial levels, permitting to observe in greater detail the actors’ behaviour and also to uncover the non-linear nature of the niche trajectory.

In this case the “country” was chosen as the territorial unit to be considered. In fact, Portugal is a small country with a centralised administrative structure and great homogeneity in terms of institutions. Policies – namely those regarding an infrastructural sector such as energy - are largely defined at country level. Moreover, Portugal is a country with limited resources, which is reflected in the nature of the networks established in this emerging field: these were not local or regional, but national (or transnational), bringing together actors with relevant resources or competences, wherever they were located. In other contexts (or other technological fields) the regional or even local levels might assume greater importance. But in this particular case, the national level emerged as the more adequate to investigate the impact of territorial embeddedness on niche development.

### 3.2 Data and methods

The empirical analysis of the overall niche space draws on two types of sources: i) data on European funded RTD projects, on publications and on patents permit to trace, in generic

terms, the spatial dynamics of the research and experimental activities conducted and networks formed, and to identify key actors[1]; ii) information on the creation of supra-national networks and collective organisations, based on documents produced by them, permits to identify attempts at structuring the niche space by conducting field-level aggregation activities. This will permit a brief characterisation of the current situation in the wave energy technological niche and offer a first, generic, overview of its trajectory.

The empirical research on activities that took part in Portugal, as part of the formation and early development of a wave energy niche, was based on the analysis of the documented actions enacted over time by actors operating in the niche, including information on research projects and research outputs, experimental activities, organization creation, business investments, research or business partnerships, participation in collective activities, policy instruments. For this purpose the analysis drew on several sets of data.

Data on publications involving Portuguese authors, patents with Portuguese applicants, European funded research and technology development projects involving Portuguese organisations, and PhDs awarded by Portuguese universities or recognised by them (in the case of PhDs obtained abroad) was purposefully collected from online databases[2]. Additional data was obtained from the websites of a number of international conference series dedicated to or encompassing the wave energy field. Data was similarly collected on projects funded by Portuguese programmes covering a wide range of activities – e.g. research and development, technology transfer, innovation, test and demonstration, human resources training, entrepreneurship, infrastructure building[3]. These data enabled us to identify the activities performed in these areas and the actors conducting them, and also permitted to start uncovering relationships. Data on business activities conducted by Portuguese firms draw on both primary and secondary sources. The former included interviews conducted with 5 out of the 6 new firms created to explore new technologies in the wave energy field[4], which focused on the process of firm creation and on firms' activities, strategies and perspectives. It also included interviews with 4 of the large energy companies with greatest involvement in wave energy, which were specifically inquired about their participation in this field, as part of an interview on their renewable energy activities[5]. Data on business activities conducted by other large companies and by foreign firms were obtained from secondary sources: their websites and other firm produced information, as well as technical reports, specialised magazines, press releases, etc. Complementary data concerning additional activities conducted by other Portuguese actors – universities and research organisations, government agencies, collective organisations - was equally obtained from their websites and from a variety of documentary sources, while data on energy policies (targeting or comprising wave energy) was compiled from government documents. A small number of short interviews with key actors and with the wave energy association were conducted in the beginning of the research, with exploratory

[1] Data was purposefully collected from EUROPA CORDIS (Community Research and Development Information Service) online database for European funded projects and from European Patent Office Espacenet database for patents, using search strategies based on wave energy related keywords.

[2] Thomson Reuters' Web of Science for publications, Espacenet and INPI (Portuguese National Patent Office) for patents, CORDIS for European funded projects, Portuguese DGEG (Directorate General for Education and Science) database for PhDs awarded.

[3] Data was searched in online repositories held by a variety of Portuguese funding agencies for most recent programmes; and manually searched in final reports and other official documents, for programmes launched in the 1980s, 1990s and early 2000s.

[4] Kymaner, E-move and ReefPower (wave conversion systems); Hydromod and BlueEdge (complementary technologies). It was not possible to speak with the remaining technology developer (Sea for Life) that was not anymore in activity.

[5] EDP Inovação, Martifer, Generg and REN-Enondas (Pilot Zone for on Wave Energy).

purposes. Participation in a number of events organised by these actors permitted to follow-up the most recent developments in the field, which were not yet documented.

This data supported a preliminary of analysis of the development of wave energy in Portugal, focusing on the identification of the actors that have been involved with the niche, on the mapping of formalized activities they have conducted in or on behalf of the niche (individually or in collaboration) and on a first assessment of the main outcomes and their implications for niche development. While we are aware that a complete understanding of the processes of niche formation and attempted upscale can only be achieved through a more in-depth appreciation of the expectations, motivations and decisions of the various actors involved, we start by focusing on some of their most visible results, i.e. documented *actions* these actors conducted along the process. This analysis is expected to raise some additional questions on *why* and *how* these actions and outcomes come to be (Verhees, et al, 2013), which will be addressed by subsequent research.

The data is analysed from both a quantitative and a qualitative standpoint. From a quantitative perspective, we assess the extent of actor participation and the intensity with which specific types of activities were conducted, and how this evolved over time. In addition, social network analysis (SNA) (Wasserman and Faust, 1994) is used to have a more precise understanding of the configuration of the networks and the position of actors.

More specifically, SNA is applied to data on collaborative projects, in order to uncover and depict relationships between organisations. Collaborative projects constitute two-mode networks that link organisations to an event - the project. From these we extract a one-mode network, considering inter-organisational networks, where a tie joins two organisations that collaborate in the same project. We build symmetric adjacency matrices, valued by the number of common projects and conduct SNA using UCINET software. Network diagrams are built using NetDraw and NodeXL software. In order to identify key actors, two centrality measures are considered: degree and betweenness. Centrality measures enable to detect more favourable network positions (Freeman, 1979). The degree centrality indicates the actors' activity level, in terms of number of ties established with other organisations, uncovering the actors who are potentially better positioned to enact more intense knowledge exchanges. The betweenness centrality indicates whether an actor is more frequently positioned between other pairs of actors, thus playing the role of a broker in the network.

This quantitative approach provides the ground for a more in-depth analysis of the processes taking place that adopts an historical perspective and relies mostly on qualitative, interpretative methods. The analysis at Portuguese level is conducted at the light of the developments taking place at the overall niche level and, whenever relevant, addresses the overlap/interplay between them.

## 4. The wave energy technological niche: the overall niche space

In the last decades, some renewable energy technologies have attempted to break out of the niches where were being developed, with diverse levels of success (Verbong et al, 2008). Some have now achieved considerable market diffusion (e.g. wind energy), supported by favourable policies and also increasingly attracting the interest of regime actors (Bergek et al, 2013), while others are still at a more incipient stage. However, interest and investment on the more "laggard" technologies has also been sustained (REN21, 2013).

This is namely the case of wave energy conversion, where the technology is far from being stabilised (Falcão, 2010; IRENA, 2014). No dominant design has emerged yet, and there is a variety of competing conversion systems being developed by different actors, mostly small technology-intensive companies. The more advanced systems have been going through intense testing, sometimes in real sea conditions, but none has gone beyond the pre-commercial stage. Major problems are still to be solved concerning both the efficiency of the energy conversion process and the capacity to withstanding the very harsh conditions of operation (Magagna et al., 2014). The difficulties experienced meant that wave energy has been particularly slow in achieving the extensive benefits promised (Jeffrey et al, 2013). But its advocates have been able to create a protective space – a technological niche – and to sustain it over long periods and several setbacks (Clément et al., 2002; EU-OEA, 2013; Hamawi and Negro, 2012).

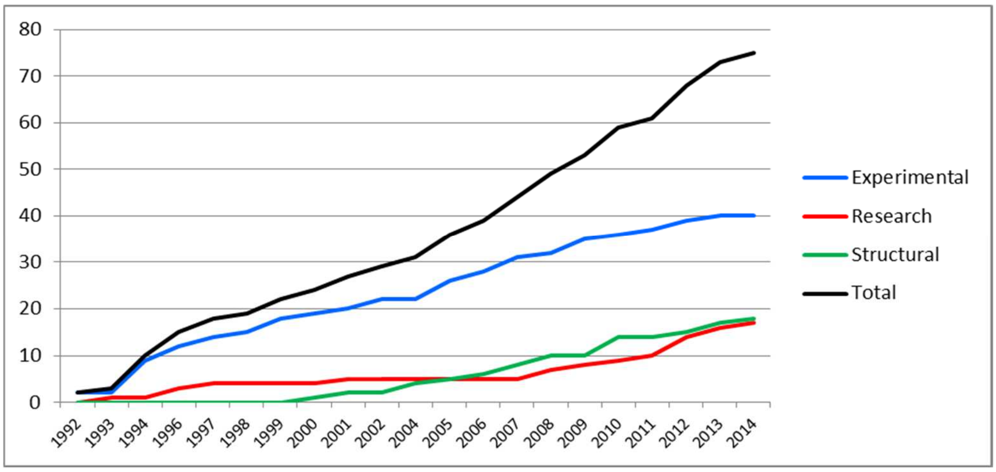
In this section we provide an overview of the evolution of the wave energy technological niche, drawing on information on activities related with knowledge production and experimental development, which give some indications on the extent of efforts developed and on the nature of actors and the networks formed over time. Data on the emergence of collective organisations and activities give some indications about the formation of a (international) community and its dynamics.

4.1 – Network formation around research and experimental activities – spatial dynamics

The dynamics of the research and experimental activities and the networks formed around them are first analysed on the basis of data on European funded research and technology development (RTD) projects. Data was collected from all the programmes for which information is available in the CORDIS (Community Research and Development Information Service) database, using a number of keywords related with wave energy.

European programmes started supporting wave energy projects in 1992, following an EC initiative targeting this field (Elliot et al, 1993). Their numbers evolved very slowly, only registering a greater increase in the most recent Framework Programmes (FP), coinciding with a greater European focus on renewable energies: FP6 (2002-2006) and FP7 (2006-2013), totalling 15 and 31 projects, respectively (Figure 1). About half of the projects have an experimental component, related to test of technologies or assessment of wave resources. Research projects have a lower weight (22%), but their numbers increased in FP7, reflecting the need to reinforce the development of more fundamental knowledge, to address persisting problems. Finally, a substantial number of projects (25%) are concerned with structural activities, such as pooling information, drawing lessons and sharing information about best practices and key obstacles, providing guidelines for policy formulation, raising awareness about the field and inducing its development.

Figure 1 - Number of RTD wave energy projects funded by European programmes (cumulative 1992-2014)




The first projects involved actors from a small number of countries, and while the range of participants have increased over time, these countries – and a core set of organisations in them - remained central. Interestingly, by the early 2000s some projects started including actors from outside Europe, particularly the US and some Asian countries, reflecting the growing interest of these regions in the field. Table 1 shows the 10 countries with higher number of project participations. The UK emerges as the leading country, having participated in 2/3 of the projects and coordinating almost half of them, followed by Portugal that participated in more than half, and, at a certain distance by Ireland, Denmark and Spain. While organisations from the first four countries pioneered the activities, Spain entered more recently but achieved a remarkable growth in a decade.

Table 1– Country participation in European wave energy projects (1992-2014) – 10+ countries

| **Countries (10+)** | **Nº Projects *Total=75*** | **% total projects** | **% projects coordinated** | **Nº participations *Total=681*** | **Nº organisations *Total=360*** |
|---|---|---|---|---|---|
| UK | 55 | 73.3% | 40.0% | 133 | 75 |
| Portugal | 43 | 57.3% | 32.6% | 86 | 27 |
| Ireland | 33 | 44.0% | 15.2% | 44 | 13 |
| Denmark | 29 | 38.7% | 37.9% | 62 | 32 |
| Spain | 25 | 33.3% | 28.0% | 53 | 36 |
| Germany | 22 | 29.3% | 9.1% | 31 | 18 |
| Norway | 21 | 28.0% | 14.3% | 41 | 29 |
| France | 19 | 25.3% | 10.5% | 30 | 15 |
| Italy | 19 | 25.3% | 15.8% | 34 | 26 |
| Sweden | 19 | 25.3% | 0.0% | 25 | 14 |

Firms represent over half of the participants. Around 20% are technology developers, the remaining being energy utilities or firms engaged in activities along the value chain. Firms have been active from the early stages, in parallel with research organisations, but their numbers took-off recently. This reflects the expansion of the niche network, in particular the capacity to attract a broader set of companies to experimental activities. Nevertheless, most firms tend to participate in few projects (several only in one) and to prevail in experimental ones. Conversely, research organisations that also have an important presence in quantitative terms (37%), and a few collective organisations, often play an additional role as knowledge conveyers, across projects and over time. This is the case of some organisations that have participated in a high proportion of the projects and are frequently present in structural ones, namely projects that have a clear focus on aggregation activities. Table 2 lists the organisations

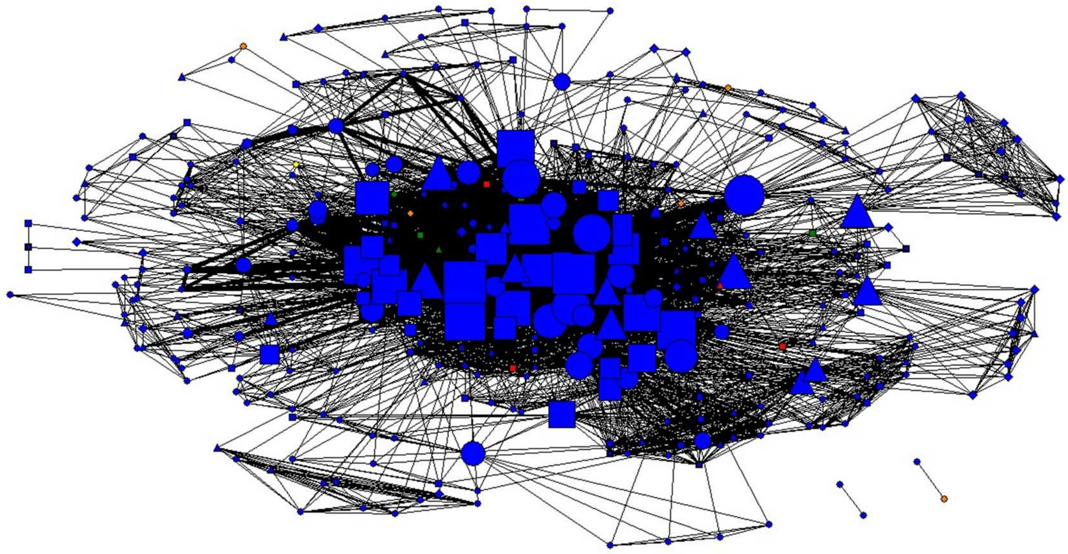
that performed more frequently this role, confirming the continued presence of actors from the countries highlighted above.

Table 2 – Individual organisations with highest participation in European projects (1992-2014)

| Organization (10+) | Country | Nº Projects | Nº Coord. | % total projects |
|---|---|---|---|---|
| University College Cork | IE | 24 | 2 | 32.0% |
| Instituto Superior Técnico (IST) | PT | 20 | 7 | 26.7% |
| WavEC | PT | 18 | 2 | 24.0% |
| University of Edinburgh | UK | 17 | 3 | 22.7% |
| LNEG | PT | 13 | 2 | 17.3% |
| Aalborg Universitet | DK | 11 | 0 | 14.7% |
| Queen's University of Belfast | UK | 11 | 2 | 14.7% |
| Fraunhofer-Gesellschaft | DE | 9 | 1 | 12.0% |
| Ecole Centrale de Nantes | FR | 9 | 0 | 12.0% |
| NTNU | NO | 9 | 0 | 12.0% |

Finally Figure 2 presents the network of organisations that participated in European projects during the period under analysis, showing European organisations in blue and those from other regions in different colours. The size of the nodes reflects the actor betweenness centrality, highlighting actors that participated in a variety of RTD projects with diverse networks compositions, acting as brokers between other actors and contributing to the structuring of the network. Figure 2 confirms the central position of a set of organisations that acted as conveyers of knowledge, a role mainly performed by research organisations (squares) - which often coincide with the ones listed above as the most active - although we can also observe some collective organisations (circles) and firms (triangles). These organisations can be described as “intermediary actors”, as proposed by the socio-cognitive perspective (Geels and Deuten, 2006). They participate in a sequence of individual projects, linking between them; and they further contribute to the learning processes by bringing the knowledge and experience thus gained into the performance of aggregation activities conducted in the context of European level structural projects.

Figure 2 - Network of organisations in European wave energy projects (1992-2014)



*Legend*: Squares – Research organisations; Triangles – Firms; Circles: Other
*Actors with highest values for betweenness centrality (brokers)*: NTU (NO), Fraunhofer-Gesellschaft (DE), IST (PT), LNEG (PT); University College Cork (IE); Ecole Centrale de Nantes (FR); IT Power Ltd (UK); Denmark Technical University (DK); Ente Vasco de la Energia (ES); University of Edinburgh (UK).

The strengthening of the learning processes in the wave energy field, and the role played by some key countries and organisations is confirmed by data on scientific publication. For this we draw on an analysis conducted by Corsatea and Magagna (2014) for the period 1998-2011, using two sources of data: ISI Web of Science for journal papers, and the proceedings database of the European Wave and Tidal Energy Conference for peer-reviewed conference papers. They uncovered a high growth rate in both cases, which was particularly impressive for published papers, which took off in the late 2000s. This increase was also associated with the appearance of some topic specific journals, which provided an additional arena for knowledge sharing. These authors also identified the organisations with highest scientific production. UK was the country with the highest rate of production, followed at a distance by organisations from Ireland, Denmark and Portugal. The most productive organisations were largely coincident with the central players in the European projects listed above.

Finally, patent data, provides additional information on more innovation-oriented activities and also permits to move the focus beyond the European area. For this purpose we use data on "International Patent Applications", filed under the Patent Cooperation Treaty (PCT), since they are likely to reflect better the intense activity taking place in the field[6] (Figure 3).

[6] Following the signature of the Patent Cooperation Treaty (PCT), inventors can file a "International Patent Application" that provides temporary protection in several countries. Although no patent is granted as a result of this application, it is an indication of intention of patenting in the near future.

Figure 3 – Evolution of PCT patent applications in wave energy by world region (publication date 1979-2014)

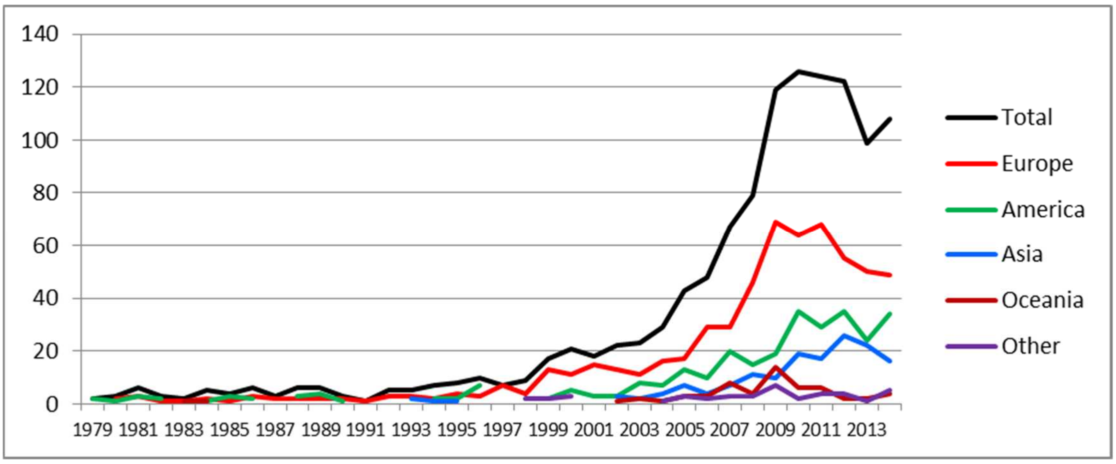



Figure 3 shows an increase in patenting in the mid-2000s. About half of the patents were filed by individual inventors, which prevailed in the early years and remained important throughout the period, even if their weight decreased in recent years. This reflects the low technology stability, which gives margin for a wide variety of solutions proposed by individual inventors. Organisational patenting is clearly dominated by firms, from all around the world. Although some research organisations can also be found (alone or in collaboration), they have much less expression and do not always coincide with the main knowledge producers. In what concerns the spatial distribution of patenting, European countries dominate with about half of the patent applications, followed by North America (US and Canada) with 23% and Asia (mostly China, Korea and Japan) with 13%. Patenting in American and Asian countries took-off more recently. In what concerns individual countries, the US is now dominant, followed by the UK, while the other European countries with strong positions in knowledge production are much less productive in terms of patenting. Among non-European countries Australia stands out, having gone through a fast development in recent years[7].

4.2 – Collective efforts of an emerging community

Collective actions on behalf of an emerging wave energy niche become more evident in the early 1990s, particularly in Europe. These actions result from the activity of a growing community that starts engaging in the collection and aggregation of information originating from a variety of experiments taking place in and across different locations. Wave energy actors were able to gain the interest of the European Commission that included wave energy in the RTD funding programmes in 1993 and supported several initiatives, namely the organisation of workshops, where knowledge and experiences were shared (Clément et al, 2002). Dedicated conferences had been taking place since the late 1970s (Falcão, 2010), but in the 1990s their scope was expanded and, over time, events such as the European Wave Energy (later also Tidal) Conferences (EWTC), started in 1993, or the International Conferences on Ocean Energy (ICOE), started in 2006, became regular discussion arenas. Similar concerns are patent in the growing number of the European-level projects concerned with structural activities, mentioned above. Examples of these are, among others, the Coordinated Action for Ocean Energies launched in 2004 (CA-OE, 2009), the 2010 ORECCA project, that produced a

[7] Space limitations preclude us to detail the organisations engaged in patenting or RTD projects in each country, in particular the great variety of companies developing wave energy systems. Information on the main players can be obtained from recent reports (e.g. OES 2014; IRENA, 2014; Corsatea and Magagna, 2014) or from the European Association webpage (http://www.oceanenergy-europe.eu).

Roadmap (ORECCA, 2011), or the recent Strategic Initiative for Ocean Energy Development (SI-OCEAN) (Magagna et al, 2014),

Another important step was the launch, in 2001, in the context of the International European Agency, of an Implementing Agreement on Ocean Energy Systems (OES) with the explicit objective of facilitating and coordinating ocean energy activities (OES, 2002). OES has become an important locus for aggregation of experiences, agenda definition and knowledge diffusion. Founder countries were UK, Portugal and Denmark, but some non-European countries - Japan, Canada and the US - joined soon after. Membership reached 23 countries in 2014 (about ½ from Europe and ¼ from Asia). Although participation is at country level, the actual representatives tend to belong to the most active organisations in the field (OES 2002-2014). Finally, in 2006 a European Ocean Energy Association was launched (under the EC auspices). It involved, from start, key companies (including some energy utilities) and has evolved to become the voice of the sector, producing a Vision document in 2013, at a moment when investment appeared to start dwindling (EU-OEA, 2013). It is currently involved in actions towards the launch of a European Industrial Initiative in the context of Horizon 2020 Programme, in which ocean energies are an important area of action (EC, 2014). Country level associations were also created in the mid/late 2000s in some European countries and outside Europe, namely in the US, Australia and Japan. Other supra-national networks and organisations have also emerged in this period.

These organisations and events have produced, over time, an intense stream of documents analysing the state of the art of technology and the opportunities and obstacles to the field and proposing directions for its development, targeting field actors and policy makers. Thus, they have been extremely active producing abstract knowledge and articulating expectations on the societal contribution of wave energy and the possible paths regarding its future development, and also adjusting them to the sometimes disappointing results. This includes namely, the growing association of wave energy the with other ocean energies, in particular offshore wind that had started achieving positive results and experiencing fast growth. This move became more evident in mid-2000s and is currently reflected in the activity of the various collective organisations, as well as on policies (European and national) that generally target “ocean energies” (e.g. EC, 2014).

This collective action reflects the formation of an increasingly connected community that is strongly international from its inception. It also indicates its active efforts towards the development of niche level learning processes. That is, to produce and share collective knowledge and to use the results of these efforts to articulate expectations, providing directions for action across the niche space and striving to attract and maintain actors and resources. It also reveals the presence of a persistent core of actors that have managed to keep the process going over time, achieving a greater niche structuration, despite the difficulties in stabilising the technology and the uncertainty this signals to resource providers. The results in terms of overall niche evolution reflect a slow and non-linear development, even if the network of actors has increased and diversified and the amount of resources available for the niche has shown a positive evolution.

This analysis provided an overview of the niche development trajectory and offered some insights into the nature of processes at work, with particular emphasis on their spatial dynamics. However, a more precise understanding of the nature of the cognitive processes performed – concerning both the production of generic knowledge and lessons, and the way these influenced the definition (or reconfiguration) of field-level visions and agendas and the expansion of supportive networks – will require a more in-depth examination of the

community level aggregation activities enacted over time (namely drawing on their outputs), as well as a detailed assessment of the role played by intermediary actors.

The collective effort towards the construction of a wave energy space was grounded on the activities being conducted in or across a great variety of locations. As also become clear, some actors, originating from some countries mostly located in one world region (Europe), were central in the process of niche formation and have remained very important along its evolution. Thus activities at country, and in some cases at regional level (e.g. Scotland in the UK), were an important element of this process. As pointed out above, territorial conditions are likely to have led to differences in the way niche development processes were conducted and in the actual contributions to the global niche development, even among the most central actors.

## 5. The development of the wave niche in Portugal

In this section we focus on the processes that took place in Portugal as part of the formation and attempted upscale of a wave energy niche. This will enable a more detailed analysis of these processes, as well as a better understanding of the impact of territorial elements on niche development.

### 5.1. Brief overview of niche evolution

The analysis started by building a detailed map and chronology of actions (actors, activities, relationships, outcomes), drawing on the different sets of data compiled for the Portuguese case, and on the qualitative information collected both from the niche actors and from documents addressing specific aspects of niche activity. This supported a more detailed analysis that aimed at: i) identifying significant social and cognitive activities that were conducted over time and delineating their spatial scope; ii) understanding the outcomes of these activities and the implications for the niche trajectory; iii) tracing specific configurations assumed by the niche processes over time, and the role played by the interplay between territorial and niche level effects.

For analytical purposes the trajectory was organised in six "periods". Criteria for the definition of the periods were relevant changes in the niche configuration, which could derive from: intensity of actor entry (or exit); changes in the nature or mix of activities (e.g. move from R&D to experimental activities); attraction of new resources and/or new types of actors (e.g. regime actors; foreign technology developers); changes in actor expectations; changes in policies. The following periods were identified and labelled according to their dominant feature:

- **P1** Before 1988 - Antecedents
- **P2** 1988-1993 - Raising awareness
- **P3** 1994-1999 - First experiments
- **P4** 2000-2005 - Early niche expansion
- **P5** 2006-2010 - High expectations
- **P6** After 2010 - Disappointment & uncertainty

Figures 4 and 5 illustrate graphically the evolution of the niche along these periods, in what concerns the formation of a network of supportive actors and the nature of their involvement (starting in P2, which effectively corresponds to niche formation). Figure 4 presents data on first entry (through formal activities) and on new actions by actors already in the niche, distinguishing, for the latter, between actions that correspond to the performance of the same type of activity (repeat activities) and of new ones. For this purpose the activities performed

are categorised in four types: research, experimental activities, business investment (including firm creation) and structural activities. The number of actors performing each type of activity is presented in Figure 5.

Figure 4 –Number of actors involved in formal activities, in each period

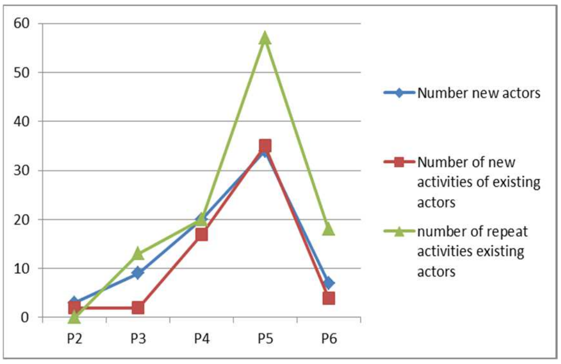
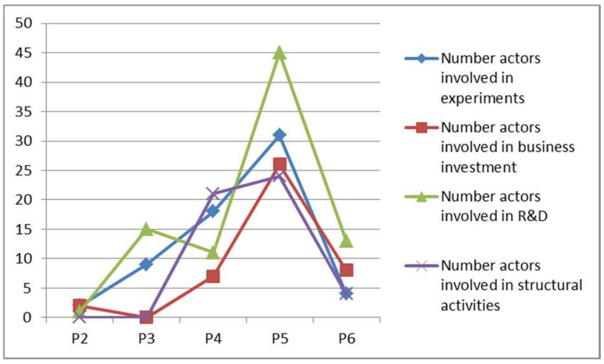



Figure 5 – Number of actors by type of activity in each period




These figures show a clear pattern of slow growth, take off, hype and decline, whereby new entry of supportive actors and the activities they perform, grow more or less steadily during the first three periods, register a sudden explosion and fall again, leaving only a "core" network active.

These patterns are explained in greater detail below, through a more detailed analysis of the processes that took place, as well as the context where these processes unfolded. The activities conducted in Portugal are also set against the overall niche space. The latter is represented, in each period, by the knowledge network formed by the organisations active in European funded RTD projects. The network involving Portuguese organisations is highlighted in red. Larger nodes represent more central actors, based on the calculation of degree centrality that indicates the actors that participated in the highest number projects and/or in large consortia. The shape of nodes denotes the type of organisation: research organisations (square), firms (triangle), other, such as collective organisations or government agencies (circle). A table characterising the knowledge network formed in each period, in terms of size (number of organisations and number of ties) and degree centrality (average, maximum and minimum) is presented in Appendix.

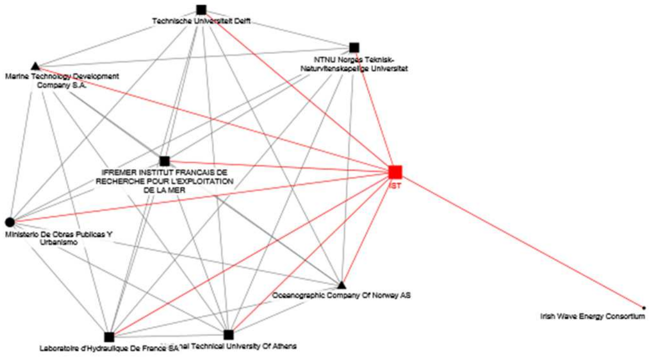
**5.2 The formation and evolution of the niche**

*Period 1 – Antecedents – Before 1988*

The first period corresponds to the "pre-history" of wave development in Portugal. An embryo of research group in this field started being formed in the late 1970s, based on a small number of scientists from an engineering university (IST). Most of these scientists, who would become central actors in the development of the niche at country level, did their PhD in the UK and maintained close connections with other members of the then emerging wave energy community. In the early 1980s the first government policy towards renewable energies is set-up (a system of generic fiscal incentives) and in 1988 there is the first great transformation in the energy system – a law that establishes the liberalisation of the electricity market, terminating the monopoly of the electricity utility (EDP) and authorising the independent production of energy, thus opening the space for renewable energy development.

*Period 2 – Raising Awareness (1988-1993)*

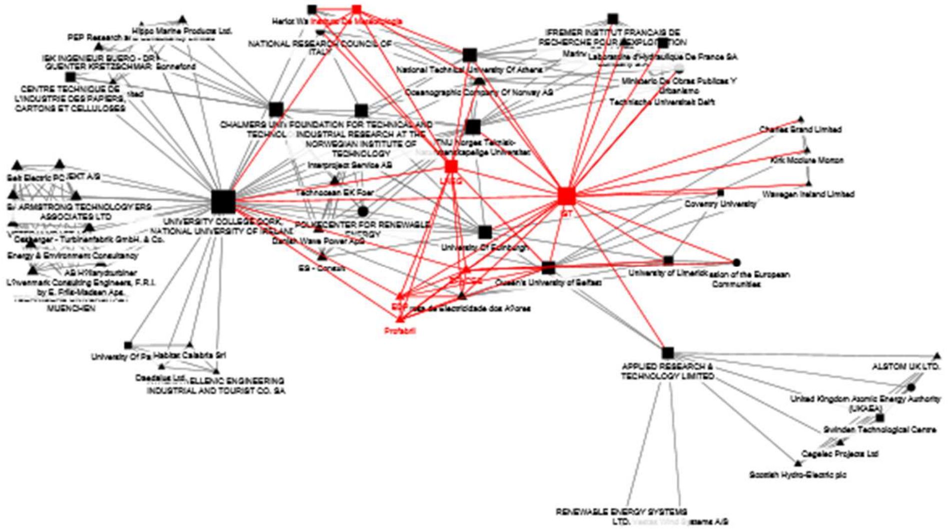
Figure 6 – European knowledge network in wave energy: organisations in projects 1988-1993




This period combines the first steps towards the liberalisation of the electricity market with the set-up of the first government programme specifically targeting the energy sector. The small group of scientists active in the wave energy field includes, besides IST, a government laboratory that will equally become a central actor (LNEG). The still limited recognition of the field in national programmes means that research activities are mostly conducted in the context of European projects, involving actors from the other "pioneer" countries. As a result of the early learning efforts of this international community, it is decided to pursue to the first large scale experimental activities. For this purpose resource evaluation is conducted in a number of locations in Portugal, UK, and Ireland with a view to building experimental sites, in the context of European projects. In Portugal, the experimental project is led by IST that, together with LNEG, also participates in similar activities in the other locations. Thus, from an early stage, "individual experiments" are conducted by a network of actors originating from different locations (Figure 6), who also start creating specific arenas for exchanging the contextual knowledge produced in these experiments (Falcão, 2010). Portuguese scientists occupy a relevant position in this network: IST is the most central organisation, being connected with all the other actors (Figure 6). In the meanwhile, at country level, the development of scientific competences pursues with new PhDs (conducted in Portugal and abroad). A first spin-off from IST is formed offering wave modelling services.

*Period 3 – First Experiments (1994-1999)*

Figure 7 – European knowledge network in wave energy: organisations in projects 1994-1999 [a]



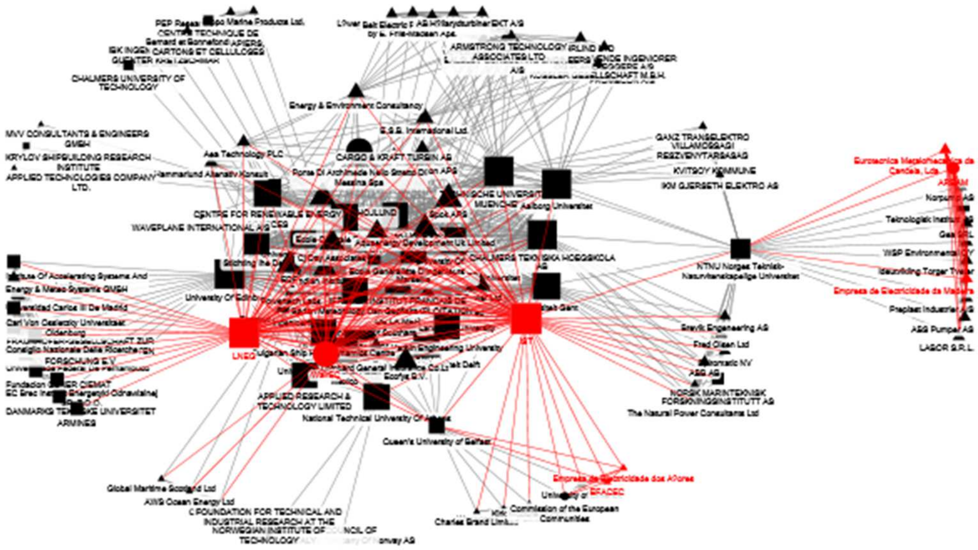

[a] *University College of Cork and IST are the most central organisations, followed at a certain distance by LNEG, Queen's University of Belfast, Azores Electricity Company (Portuguese utility), Technical University Athens and NTNU.*

Following the positive results from resource evaluation, it is decided to pursue with the set-up of the world first experimental site – the European Wave Energy Pilot Plant in the Portuguese Azores island of PICO. This project is a critical step in the expansion of the niche network in Portugal. In fact, the scientists behind the project are able to attract two important regime actors: the utility (EDP) and the main national energy equipment manufacturer. This is the first move of the utility into a field where it would play a significant role. The participation of scientists from other countries ensures that knowledge inputs and learning outcomes go beyond the local level. In a similar vein, a few years later, IST participates in a project to install an experimental site in the UK (the Limpet pilot plant). These pioneer projects are an important element in the learning process at global niche level, both in technological terms and in what concerns the involvement of new actors along the value chain.

In addition to experimental activities, the group of pioneer IST and LNEG scientists go on conducting fundamental (modelling) and applied (e.g. turbine development, resource assessment) research, contributing to reinforce the knowledge base. They maintain important positions in the expanding international scientific community (largely centred in the North Atlantic countries), where they are now joined by the regime actors (Figure 7). But research is still mostly conducted in the context of European projects. In fact, despite the launch, in 1994, of a dedicated "Operational Programme for Energy", only by the end of the period (1999) we find projects supported by national funds.

*Period 4 – Early Niche Expansion – 2000-2005*

Figure 8 – European knowledge network in wave energy: organisations in projects 2000-2005 [a]



[a] *IST and University College of Cork, LNEG, University of Edinburgh and Munich Technical University are the most central organisations*

The 2000s represent a major turning point in the Portuguese policies towards renewable energies. Ambitious targets are established in response to the EU Directive on Renewables (2001/77/CE) and a new Programme (E4 - Energy Efficiency and Endogenous Energies) is launched, establishing objectives for renewable energy production and mechanisms to support it. Among these is the introduction of feed-in tariffs, including a special tariff for wave energy, and support to investment projects. In spite of this, the number of wave projects supported remains relatively small, with the largest amount of investment going to the more mature wind energy technology, which is starting to diffuse in the country (Bento and Fontes, 2015).

But the niche activities conducted by Portuguese wave energy actors intensify, encompassing different cognitive processes and spatial levels. Involvement in transnational activities increases, including both the conduction of more fundamental research and the participation in EU funded experimental projects, led by foreign firms in various other locations. IST and LNEG also participate in several projects and other actions that start being launched at European level with “structural” objectives, including projects whose explicit goal is to aggregate results from individual projects and other experiences taking place in different countries, convert them in abstract knowledge, and share it within the community. Some of these crystallise in the creation of stable networks or supra-national organisations, which are also concerned with producing (or reconfiguring) a vision for the field. IST and LNEG researchers remain central in the growing scientific community (Figure 8). They also occupy an important position in the new organisations: e.g. Portugal is founding member and first chair of IEA-OES, where it is represented by LNEG (OES, 2002). They are also actively involved in the organisation of a variety of events that act as arenas for knowledge circulation or wave energy promotion. Moreover, other Portuguese actors (including regime and policy actors) start joining the international network, often as part of projects led by these pioneer organisations.

At country level, niche structuring increases with the creation, in 2003, of a wave energy association – WAVEC - involving research organisations and firms. WAVEC launches awareness and lobbying actions at country level and participate in structural EU projects, joining (and

sometimes replacing) the research organisations that traditionally led the Portuguese participation in these activities (WAVEC, 2008)[8].

The process of niche development at country level registers a turning point in this period, due to a new set of events. As several wave energy conversion systems reach a stage where larger scale testing in real sea conditions is required, some foreign technology developers start choosing Portuguese locations to conduct their experimental activities. Three main reasons can explain this decision. First, the country natural conditions that elect it as a promising location for wave energy production (WAVEC, 2004). Second, the extensive international connections and reputation of the main actors. Their position in the global niche community enables them to identify potential opportunities and to gain the interest of the foreign actors, while their previous record signals strong scientific and technical competences and local experience. Finally, the favourable policies for renewable energies, including wave energy. These are critical in a field where experiments require expensive infrastructures and a combination of different activities along the value chain (Falcão, 2010). By the end of the period, one experimental project has been launched and a couple of others are announced. These projects assume the form of joint ventures between the foreign technology developer and local large companies and are highly subsidised, usually involving a combination of national and European funds. The interest of established companies (often already involved in other renewable technologies) in wave energy projects is an additional source of attraction, since they can provide resources and offer legitimacy towards capital providers and other firms along the value chain. This model will continue being adopted in subsequent periods. As a result, the niche network expands both in number and variety of actors and in the spatial scope of activities.

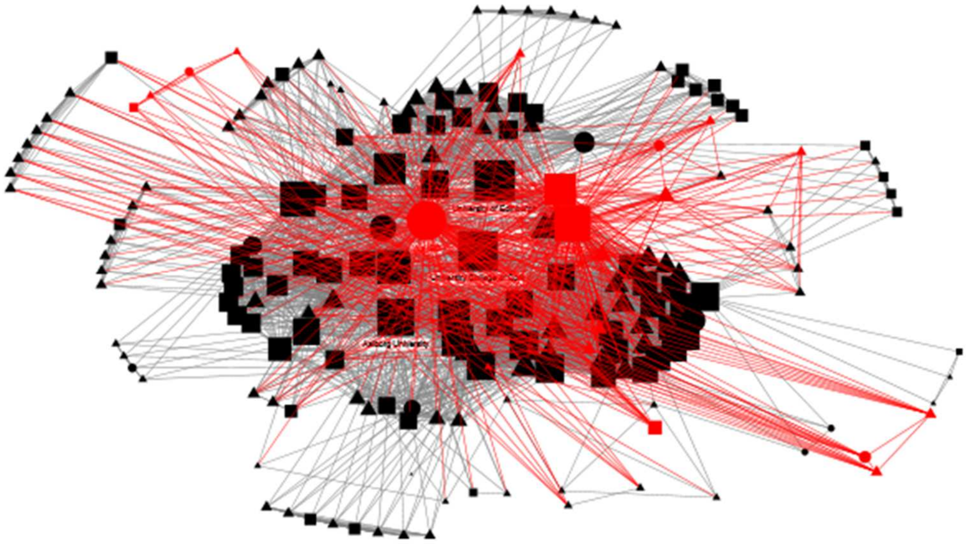
Despite the growing interest in wave energy, technology development conducted by Portuguese firms is still limited. One spin-off is created to exploit university technology and one large company, already active in the wind energy field, starts developing its own technology, in collaboration with universities. One experimental project involving only national organisations is announced, but does not pursue till the end. At the same time the PICO pilot plant experiences problems and a recovery project is launched.

It is possible to argue that at the end of this period a national constituency is already being formed around wave energy in Portugal. Because R&D activities are still critical, scientists remain central actors. But other actors have now joined the network, either gained to invest resources or involved in the development of technologies. They include a small group of regime actors, who play a significant role, given their investment capacity and the legitimacy that their presence bestows to the field. They also include a set of foreign technology developers, whose presence permits to extend the scope of learning from experimental activities. However, it is also possible to argue that a substantial part of the activity of what is sometimes described as the “country niche” is in fact taking place beyond the country territorial boundaries. That is, the emerging national network is complemented with the transnational networks that connect Portuguese actors to projects conducted elsewhere; and with the supra-national networks, concerned with aggregation activities, to which the core actors belong. This international positioning of niche actors is critical for strengthening their position at country level, increasing their capacity to enrol local actors and to influence the setting-up of favourable policies. In fact, due to the participation of Portuguese actors in vision building and agenda setting, global niche processes have an immediate impact at country-level, namely leading to the development of high expectations.

[8] WAVEC activity is extensively documented in its website: http://www.wavec.org/en

*Period 5 – High Expectations – 2006-2010*

Figure 9 – European knowledge network in wave energy: organisations in projects 2006-2010 [a]



[a] The number of organisations precludes the use of labels for nodes. WAVEC and University College of Cork are the most central organisation, followed by University of Edinburgh, Aalborg University and LNEG.

The government bet in renewable energies was reinforced with the launch, in late 2005, of a National Strategy for Energy (ENE 2010, prolonged in 2009 by the ENE 2020 and the Action Plan for Renewable Energies (PNAER)), where renewable energy is presented as a priority and described as a driver of country development. Country targets are revised upwards. The ocean also becomes a focus of policies (National Strategy for the Sea) that aim at the development of an Ocean Cluster, which includes energy, generating a renewed interest in wave energy.

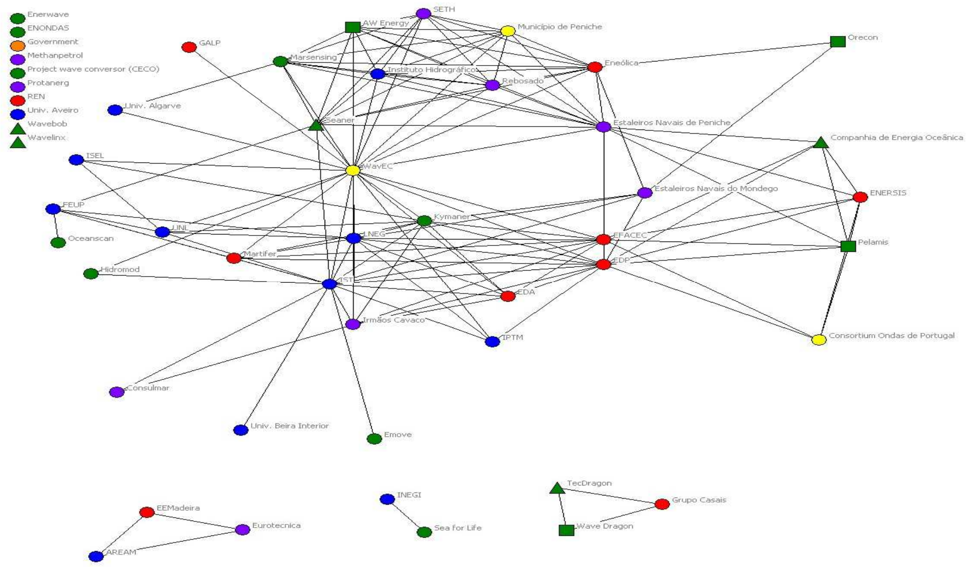
As part of this favourable political environment, there is a growing consideration of the country potential for attracting foreign technology developers to test their technologies off the Portuguese coast. These are a mobile set, highly dependent on favourable policies, availability of infrastructures and of investors that enable them to endure the high costs of the sea level experimental projects (Løvdal and Neumann, 2011). The government, encouraged by national niche actors, decides to create a Pilot Zone for Wave Energy - i.e. a fully equipped test and demonstration infrastructure - that differs from similar facilities set-up in competing countries, by admitting both experimental projects and small early stage commercial projects.

The announcement of the Pilot Zone leads several foreign technology developers to express interest in testing their technologies there. The message put forward by these firms is that their technologies are approaching stabilisation and that these experiments, which move them from the relatively sheltered early test environments to real sea conditions, will swiftly lead to commercial installations. This expectation raises the interest of several established Portuguese companies and new joint ventures are prepared. Among these stands the utility EDP that is engaged in several projects and becomes a very proactive advocate of the field, deploying its considerable resources and political power. Some of these companies also invest in systems being developed in other countries, or in projects that are expected to create opportunities for future technology deployments in Portugal. Experimental projects also start involving Portuguese firms located along the value chain (e.g. metalomechanicals, shipyards, sea equipment and logistics). They also show an early concern regarding environmental impacts and the need to avoid interference with other activities that share the ocean space. These individual experiments provide important learning opportunities, concerning the technological

and organisational complementarities that need to be created in order to obtain a fully operating system (Markard and Hekkert, 2013) and the actors' alignment required to achieve it. Results and lessons learnt from these experiments circulate across projects and locations, given the presence of intermediary actors in several of them.

The involvement of a variety of new actors leads to a sudden expansion of the network centred in Portugal (Figure 10). It also contributes to reinforce the European knowledge network, where Portuguese organisations, such as LNEG and WAVEC strengthen their central position (Figure 9). Portuguese actors also continue to be highly active in the setting-up of community level infrastructures where knowledge circulates and debate takes place, and where aggregation activities are performed. This includes, for instance, the establishment of regular dedicated conferences (where they belong to scientific or organising committees), the reinforcement of OES aggregation activities, through the expansion of its work programme (OES, 2006-2010), or the creation of the European Ocean Energy Association, with WAVEC in the board of directors.

Figure 10 – Organisations involved in wave energy activities in Portugal in P5[9] (2006-2010)




*Legend*: Circles – Portuguese; Squares – Foreign; Triangles – Joint ventures PT/foreign
Colours: Green – niche firms; Red – incumbents; Purple - value chain; Blue – research; Yellow - collective

At country level, the expansion of niche activities does not necessarily lead to a substantial increase in the resources available to local organisations. There is a small rise in the number of R&D projects funded by national programmes, and also in patenting, by universities and new ventures. However, the number of Portuguese companies developing proprietary systems remains very small. Despite the availability of public funding that support the early stages, these firms experience difficulties in up-scaling their technologies (and thus effectively testing them), given the high investments and the limited interest of private investors - who prefer the technologies (potentially) closest to market presented by foreign developers – and the absence of venture capital[10]. This reduces the scope for local development and also for the emergence of radically new designs being pursued by some firms, which can be particularly important when technologies are still far from stability (Jeffrey et al, 2013).

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[9] Include the individual organisations identified as active in Portugal in the period. Networks were only built for organisations involved in joint activities (formalised). The remaining are shown as isolated.
[10] Interviews with Kymaner, Reef Power and E-move.

The period started with high expectations for the development of wave energy in Portugal. The network had extended, involving a growing number of actors prepared to invest in the field. Moreover, wave advocates had been able to capture the interest of both government and regime actors to a narrative that stressed the country's favourable conditions, and the opportunities opened by a first mover advantage in a new field full of potential and with strong synergies with other ocean activities (Wavec, 2004). The implicit strategy was that the country could profit from the capacity to assist experimental projects, positioning itself for becoming a central location for wave energy production. The creation of a supportive industry around this activity (a "wave cluster") and the rejuvenation of traditional sectors (such as shipyards) and declining fishing communities were also part of this vision. Several elements appeared to be in place: strong international networks led by reputed scientists; a favourable energy policy; the Pilot Zone being installed and a number of experimental projects being negotiated or starting.

However, things did not progress as expected. First, the Pilot Zone, a central element of this strategy, registered delays and, by the end of the period, its set-up was not yet completed. Thus several projects ended-up being diverted to other countries (or did not pursue at all) frustrating the prospects of the local companies that had invested or proposed to invest in them. Second, expectations about the development of the technology grossly underestimated the problems to be faced in the harsh conditions of real sea experiments. Thus, the outcomes of the projects that did advance were much below expectations.

An exemplary case is the Pelamis project for the "first wave farm" [11], presented as leading to energy production in the near future and thus regarded as a potential basis for the "wave cluster". The government makes it a flag project and several companies – led by the utility EDP – invest in it. Thus, the quick failure of the system has a strong impact. EDP faced with a third negative outcome in its wave energy projects abandons the field and moves, with its partners, to the less uncertain field of deep-water offshore wind, where it can use assets and experience from the wave field, combined with its extensive experience in wind energy.

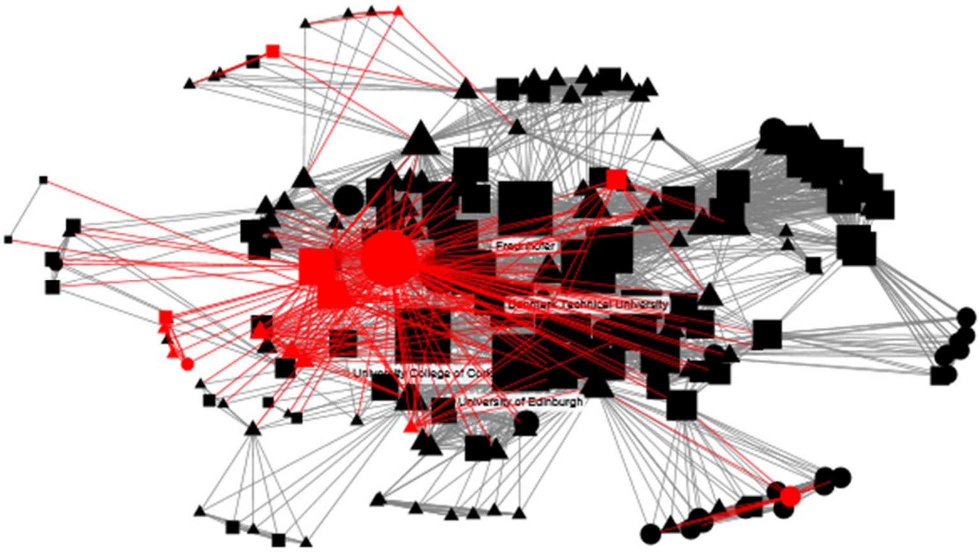
By the end of the period only one experimental project involving a foreign company is pursuing as planned, registering some success and advancing to a second phase - Waveroller promoted by the Finish AW Energy, in a joint-venture with the Portuguese Eneólica[12]. But this is an exception. The disappointment follows the "hype" (Bakker and Budde, 2012) and the supportive country network dwindles.

[11] Pelamis Wave Power went out of business in December 2014, but information about this particular experiment can still be found at the EU funded AquaRET dissemination project webpage: http://www.aquaret.com/images/stories/aquaret/pdf/cswavepelamis.pdf

[12] Information on Waveroller can be found at http://aw-energy.com/. The system remains in operation until this day. A new project for installing a (pre)commercial scale plant was funded by the NER 300 European scheme in 2014 (http://ec.europa.eu/clima/funding/ner300/).

*Period 6 – Disappointment & uncertainty (2011 onwards)*

Figure 11– European knowledge network in wave energy: organisations in projects 2011-2014[a]




[a] The number of organisations precludes the use of labels for nodes. WAVEC is the most central organisation, followed by University College of Cork, University of Edinburgh, Fraunhofer Institute, Denmark Technical University.

The problems experienced by the wave energy niche are suddenly aggravated by the economic crisis, which leads to the country bailout. This also drives a change of government and of policy: renewable energies stop being a priority, targets are revised downwards and there is an explicit divestment from "less competitive energy technologies", which includes wave energy (Revision of Action Plan for Renewable Energies - PNAER).

For the niche, the abandon of EDP and its partners is a strong blow in the credibility. Combined with continued delays in the Pilot Zone and the consequent abandon of the few waiting projects and with the gradual withdrawal of policy support, this definitively clouds the high expectations created around wave energy. No new experimental projects are launched. Investment by local companies stops, financial problems adding to disappointment. Wave energy projects disappear from national funding programs. New ventures experience increasing difficulties in obtaining financing for developing or testing their technologies. They suspend activity or search for alternative areas of application, when the technology allows it[13].

The withdrawal of support forces a strategic re-orientation. As part of their attempts at "repair work" (Geels and Raven, 2006), core niche actors search complementarities with other technologies that are achieving greater success and can help them overcome the current constraints, and also attempt to link to faster developing markets (Geels, 2005). Thus, they move the focus to "ocean energies", following a movement already visible in Europe, but also attempting to capitalise on EDP positioning in deep-water offshore wind energy, and to build synergies with these and other ocean related activities that remain central in country policies (launch of Action Plan – Sea). This effort to revitalise the country level network and to restore the image of wave energy, culminates in 2014 in the widely participated development of a

[13] Sea for Life and Reef Power are not operating anymore and Kymaner describes itself as being in "stand-by". E-move tries to apply its conversion technology to the wind field. Hidromod and Blue-Edge go on developing the other lines of business allowed by their competence base.

“Roadmap for Offshore Energies”, that is expected to provide a new vision and directions for action, with the purpose of both influencing policy decisions and (re)engaging relevant actors (OTEO, 2014).

While activities and networks dwindle at country level, we observe a continued capacity of the overall niche advocates for sustaining visions of future potential, attracting large regime actors and maintaining political support (EU-OEA, 2010, 2013; EC, 2014; OES 2013). Surviving core Portuguese actors benefit from these conditions to continue participating in a variety of foreign, transnational and supra-national activities - indeed WAVEC is now the most central actor in the European knowledge network (Figure 11). Even if the number of participating organisations, and also of those in central positions, diminishes, core actors retain their involvement in the supra-national structures where global level activities are performed. This positioning is also instrumental to support their attempts to reinstate wave energy at country level. Thus, to some extent, Portuguese actors are back to the early stages, where transnational networks sustained their niche activities at country level.

**5.3 Discussion**

The above analysis of activities that took place in Portugal or involved Portuguese actors offers some insights into the social and cognitive processes that underlie the construction of a wave energy niche space. It equally permits to gain some insights into the spatial dynamics of these processes. In particular, it permitted to examine how territorial conditions influence (and in some cases are influenced by) niche development processes.

Portuguese actors were among the pioneers in the creation of a protected space for the emerging wave energy conversion technology. This early contribution was partly based on country related factors – natural resource endowments, economic and scientific orientation to sea-related activities – which might have also been behind similar activities in other North Atlantic countries. The pioneering activities being conducted in these locations led to the emergence of a proactive group of wave energy actors, from different origins, which pooled efforts from early years. This resulted in the formation of a (growing) transnational community that worked together in research and experimental activities, developing individual projects that frequently built on each other, or involved actors present in different networks, thus promoting the circulation of knowledge produced and lessons learnt. The early emergence of intermediary actors and formalization of arenas for debate - also mostly enacted by pioneer organisations - favoured the conduction of field-level aggregation activities. These were determinant to guide the niche trajectory and to articulate a compelling vision of future benefits that attracted support from policy makers. These activities permitted a (slow) niche structuration and, together with the presence of a close-knit core community, enabled the niche to withstand the difficulties associated with a progress much below expectations.

Turning again to Portugal, the case shows that some country-related factors permitted an acceleration of the niche development. One was the presence of favourable government policies. The other was the particular configuration of the transition process that made regime actors more open to the opportunities arising in wave energy and favoured their participation, bringing resources and legitimacy. Such a favourable environment permitted to reinforce the niche network and extend its spatial scope. It also permitted the development of local learning processes - concerning both technology functionalities and the type of social structures and institutional arrangements that could support niche upscaling. But this acceleration, even if partly based on territorial factors, capitalised on the spatial features of the overall niche, in particular the fact that the niche community was highly international, that activities were routinely conducted by networks of actors from different origins and that interactions and

mobility between geographical locations were common. In addition, it benefited from the central position of Portuguese actors that were both involved in “local” experimental activities in various locations and engaged in “global” aggregation activities, thus playing an important role as intermediary actors.

From an overall niche perspective, the attempted niche upscale conducted by Portuguese actors had a strengthening effect on the niche as a whole (Spath and Rohracher, 2012). In fact, at some point Portugal was an important arena for the development of wave energy: as a setting for a variety of experimental projects that produced different learning outcomes; as a source of knowledge that circulated in the community, across projects and through actor participation in aggregation activities; and as a “showcase” and an inspiration for vision building.

However, the analysis also shows that the same type of territorial factors that contributed to accelerate niche development were responsible for its decline at country level. In what concerns policies, implementation delays and sudden withdrawal of support, by reducing the country attractiveness to mobile foreign actors and by limiting the scope of action of national actors, caused major damages (Verbong et al, 2008). In what concerns the involvement of powerful regime actors, this case evinces the risks of their excessive protagonism, which leaves the niche vulnerable to their strategic shifts (Smink et al, 2013). It also shows the impact of events taking place at the landscape level (Geels, 2002), since these effects were exacerbated by the financial crisis.

From the country standpoint, this set of events dealt a strong blow to the niche activity of Portuguese actors and effectively thwarted the country endeavour of becoming a central player in a future wave energy system. From an overall niche perspective, the downfall of the activities taking place in the Portuguese territorial space or enacted by Portuguese actors led to the shrinking of the niche space, with the reduction of the number and variety of experimental activities and the withdrawal of a component of the network (Geels and Raven, 2006). Nevertheless the continued participation of core Portuguese actors in experimental and aggregation activities - through their involvement in transnational and supra-national networks - lessened the impact of these territorial effects on the niche community and its “global level” activities. Moreover, the positioning of these actors may contribute to draw some generic lessons from this particular combination of events. On the other hand, such positioning is also important from the country standpoint, since processes taking place at global level can support niche actors’ attempts to readjust the vision and expectations and to reconstruct the country level network.

The evolution documented above provides a good illustration of the non-linearity of the niche trajectory (Geels and Raven, 2006). The analysis of the Portuguese case also permits to suggest that specific territorial conditions may impinge on the relationship between expectations, learning outcomes and the subsequent evolution of the niche processes. That is, they may potentially amplify the effects (positive and especially negative) in locations whose specific configurations of actors, institutions or policies render them more receptive to the voicing of positive expectations, or vulnerable to the negative outcomes that frustrate such expectations. On the other hand, it also suggests that the multi-spatial nature of the niche space may make it more resilient to these specific territorial effects, permitting to absorb them and eventually turn them in generic lessons to guide future developments. However, these preliminary insights need to be further explored in a wider number of cases.

## 6. Conclusions

The paper proposed that technological niche formation and development is a multi-spatial process and developed a conceptual framework to support this assertion. This framework draws on the socio-cognitive perspective to niche development and extends it by introducing an additional dimension – space. This permitted us to retain the powerful notion of a niche space that encompasses the variety generated by local projects and also transcends them through social and cognitive processes that generate an increasingly structured "global niche level". But it also permitted to strengthen it, by grounding these processes on the territorial and relational space(s) where niche actors act and interact, both within the niche space and across it, by linking-up with regime actors.

As a result, the technological niche is defined as constructed by the actions and interactions of a variety of actors that conduct different types of activities at and across different spatial levels. This multi-spatial dynamics effectively entails an interplay between a niche relational space constructed by niche actors along their "local" experimental and "global" aggregation activities (Geels and Raven, 2006), and the territorial effects introduced by the embeddedness of these actors and their actions in particular geographical and institutional settings (Hess, 2004). The niche trajectory is expected to be shaped by the processes taking place at these various levels.

This framework was applied to the case of the wave energy technological niche, by combining a generic analysis of the evolution of the "overall niche", with a more detailed analysis of the processes taking place in a specific country, Portugal, which were addressed from a country (territorial) perspective and set against the development of the whole niche.

The analysis has confirmed that the early construction of an overall niche space was supported by the extensive transnational activities of an emerging community, as well as by the early creation of supra-national networks and infrastructures concerned with global aggregation activities, agenda setting and vision building. It has also revealed the interplay between territorial and niche level effects. On the one hand, the "favourable conditions" that emerge in some locations are partly shaped by processes taking place at the overall niche level. On the other hand, events taking place in some particular locations can influence the trajectory of the overall niche. They may contribute to accelerate it, by reinforcing expectations and strengthening the network and also providing learning opportunities that enable a greater structuring of the technology trajectory (Spath and Rohracher, 2012). Or, on the contrary, they may provide negative lessons that require a reconfiguration of expectations. Thus, it is possible to conclude that the development of the technological niche is shaped by processes taking place at a multiplicity of levels which both build on and influence each other.

These results, albeit still relatively exploratory, contribute to the on-going debate on the role of space in niche development and more generally in socio-technical transitions (Coenen et al, 2012, 2010; Raven et al, 2012), permitting namely to start answering to the claim that it is necessary to address "the compatibility between a relational conceptualisation of space and the simultaneous acceptance of the local embeddedness of relations" (Hansen and Coenen, in print: 10). These conclusions need now to be further explored on the basis of more in-depth analysis of the processes taking place at the "overall niche level", as well as a better understanding of the its interplay with the territorial dimension, namely through a comparative analysis involving other national (or regional) contexts.

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APPENDIX

Characterisation of knowledge network in wave energy (European funded RTD projects) by period

| | | Period 2<br>1988-1993 | Period 3<br>1994-1999 | Period 4<br>2000-2005 | Period 5<br>2006-2010 | Period 6<br>2010-2014 |
|---|---|---|---|---|---|---|
| Number of organisations | | 10 | 72 | 121 | 195 | 213 |
| Number of ties | | 37 | 269 | 1481 | 2614 | 2435 |
| Degree centrality | Average | 0.206 | 1.672 | 8.817 | 16.656 | 15.106 |
| | Maximum | 9 | 42 | 87 | 199 | 183 |
| | Minimum | 1 | 2 | 1 | 1 | 2 |